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SURVEY OF SONIC BOOM PHENOMENA FOR THE NON-SPECIALIST

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16. Abstract

The purpose of this document is to make available to the non-specialist and non-scientist a review of the technical concepts underlying the work done in the field of sonic boom research. It contains a non-technical discussion of the acoustic mechanisms which are fundamental in sonic boom phenomena, using photographs of water wave analogues. Then the report discusses a variety of basic aspects including: generation, propagation, minimization, human response and social criteria. structural and wildlife response, threshold Mach number operations and simulation methods. The report sites many references and draws extensively on a recent review for investigators in the field of sonic boom prepared by L.J. Runyan and E.J. Kane.

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PREFACE

The purpose of this report is to make available to the non-specialist and non-scientist a review of the technological concepts of the work done in the field of sonic boom research. It has drawn extensively from the volumes by Runyan and Kane (reference 63 and 64) which contain a history of the field written for use by engineers and scientists and a comprehensive collection of condensations of the original research papers. The present work retains, insofar as possible, the subject sequence of the Runyan and Kane reports and quotes extensively from them as well as from their sources.

The author also wishes to acknowledge the suggestions made by Mr. Thomas H. Higgins, Technical Monitor.

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NOTICE

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1. Physical Nature of Sonic Booms

This report has, as its purpose, the review of the important technological work done to date on the subject of sonic boom, and the presentation of facts in a format which is accessible to the non-specialist and the non-scientist. Many of the concepts and their recent applications have made use of fairly specialized and complex mathematical techniques, the presentation of which would create major difficulties for non-specialists. An effort will therefore be made in this review to translate the relevent concepts, if not the mathematics, into terms of physical mechanisms which are more generally familiar. Such concepts may suffer from loss of precision, for which the author apologizes and asks the readers' forbearance.

We are all familiar with the concept of wave motions in the world around us. As children, and even as adults, many of us have played with the steel coil toy known as a "slinky" and have caused and watched waves race along the coil and reflect back from the end. This is a good example of wave motion in one dimension. Pebbles dropped on the surface of a quiet lake generate ripples that propagate out in perfect circles and have been a source of fascination through the ages. This is an example of wave propagation in two dimensions. Propagation in air of minute pressure fluctuations known as sound is probably the simplest three dimensional wave phenomenon. Its nature, however, is not as self-evident as that of water wave motion because our ears offer us only a fraction of the data that our eyes can amass in their interpretation of the lively reflection patterns that we see on the rippling surface of a pool.

Fortunately, there are many acoustic phenomenon including that of sonic boom, which are similar in nature to phenomena which are commonly observed on water, so that we can often use the latter as means of visualizing and better understanding the former.

Acoustic Background to the Sonic Boom Phenomenon

We might begin our discussion with a standard dic-

tionary definition of sound, as that which can be heard or can produce the physiological sensation of hearing. Acoustics, as the science of sound, deals with the manner in which sound is produced in the ear by pressure fluctuations in the environing atmosphere, with the manner in which the pressure fluctuations propagate through the atmosphere, and with the mechanism by which the pressure fluctuations are generated at some source of excitation. The most common physical mechanism for generating a pressure disturbance is the mechanical motion of solid surfaces (e.g., a vibrating cone in a loudspeaker or a vibrating sheet of metal on a noisy machine). In addition, the non-uniform flow of gases into a region (e.g., flow from the exhaust of an unmuffled motorcycle engine, the turbulent jet exhaust from a tank of compressed air or from a jet engine) and the unsteady liberation of heat (as in a turbulent oxyacetylene cutting torch) are examples of other fundamental mechanisms for producing pressure fluctuations in the atmosphere.

All of these mechanisms have in common the fact that they produce in the molecules of the surrounding air an acceleration, that is, a change or fluctuation from the condition of rest or uniform velocity.

The air, being an elastic medium, in the same sense that a steel spring or a rubber band is elastic, then transmits the disturbance away from the source, to the near as well as distant surroundings, in the form of waves. When these waves reach a listener or a microphone, they are converted into sensations or signals which can be interpreted for meaning or for annoyance.

Our ears are most sensitive to pressure fluctuations in the range of frequencies of 1,000 Hertz to 4,000 Hertz (oscillations per second) and although we are aware of a much larger range from 40 to 16,000 Hz, the sensitivity in these upper and lower regions drops off very markedly. Now the

higher frequencies are produced by air which has been accelerated very suddenly, while the low frequencies are produced by air which has been accelerated slowly and smoothly. This partially explains the fact that a smooth body in low speed uniform motion creates so little noise. Thus, despite the fact that the pressure field about a glider wing must be sufficient to carry the glider, the air particles through which it flies are accelerated very slowly and begin to move around the glider and wings, long before the glider arrives in the vicinity of the particles. The impulses which produce this acceleration of the air particles originate on the glider surfaces and travel with the speed of sound to the particles in question. A slow moving body, therefore, gives the air around it plenty of time, so to speak, to speed up and get out of the way.

In the case of a fast body, in particular a body moving faster than sound, the air particles along the flight path have no advance warning to get out of the way and so they are accelerated instantaneously from zero speed to that imposed by the outward displacement along body surfaces of the wings and fuselage. The steep fronted wave so created is known as a shock wave and contains energy at all frequencies including those of higher audibility. The prow wave spreading away on the water surface from a fast moving ship is a shock wave which is the analog in water surface waves to the shock wave in air. The spring or restoring mechanism in surface water waves is provided by the effect of gravity in pulling down the wave crests and pushing up the troughs. Therefore, the underlying physics of surface water waves is not identical with acoustic waves and, furthermore, the waves move in two dimensions rather than in three. Nevertheless, some of the similarities between surface water waves and acoustic waves are striking and are useful in visualizing the latter.

Figure 1.1a is a photograph of ripples made on the surface of a shallow layer of water. The disturbance source

FIGURE 1.1a

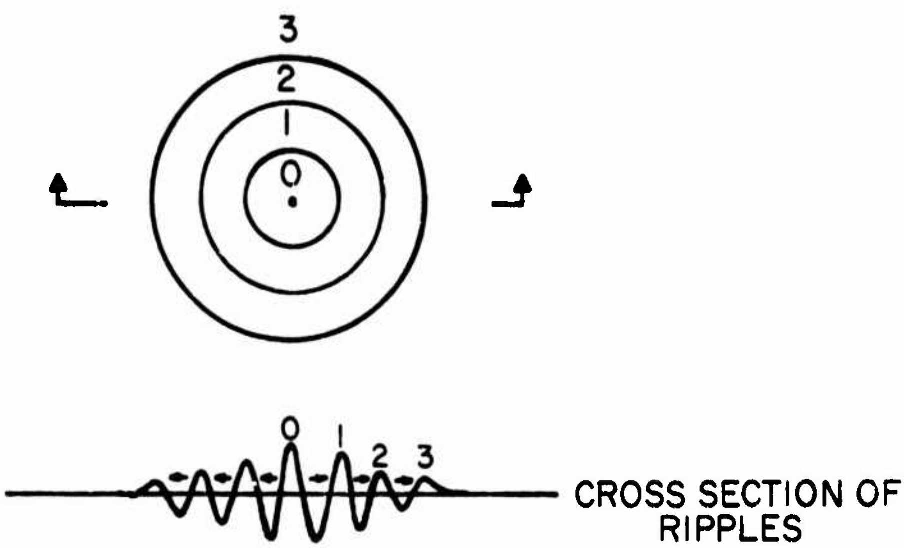


FIGURE 1.1b

is a pulsating jet of air which impinges on the water surface. In this case, the position of the source is held fixed and the ripples propagate out in perfect circles. (The viewing angle of the camera produces the elliptical foreshortening effect.) The rectangular grid in the background was included to furnish an idea of the relative wave heights, as judged by the resulting waviness.

Figure 1.1b is a sketch corresponding to this case, showing the circular wave crests, and a cross section to suggest the amplitude distribution. Each wave crest is numbered proportional to the elapsed time from moment of origin.

Figure 1.2a is a photograph made by the same process as above for the case where the source is made to move horizontally at a speed less than the ripple speed. We note that the waves are now bunched up in the direction of the source motion and spread out to the rear. This bunching up corresponds in acoustics to the Doppler effect whereby the pitch of a steady sound emitted by a fast moving vehicle is higher when the vehicle approaches than when the vehicle passes and recedes.

Figure 1.2b is a photograph of the same physical situation, but made by a different optical technique, which shows the perfect pattern of circles.

Figure 1.2c is a sketch illustrating the relationship of the movement of the successive points of origin of the ripples, and of their successive positions. The cross section illustrates the bunching up of the wavelets in front and the corresponding buildup of intensity.

Figures 1.3a and 1.3b are photographs illustrating the case in which the source is moving faster than the wave speed ("supersonic"). The zone of disturbance is now re-

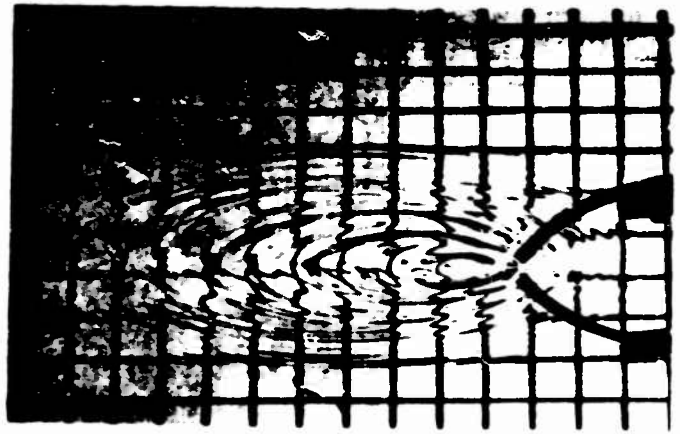


FIGURE 1.2a

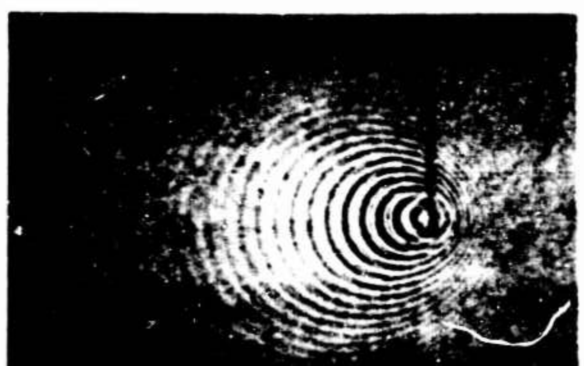


FIGURE 1.2b

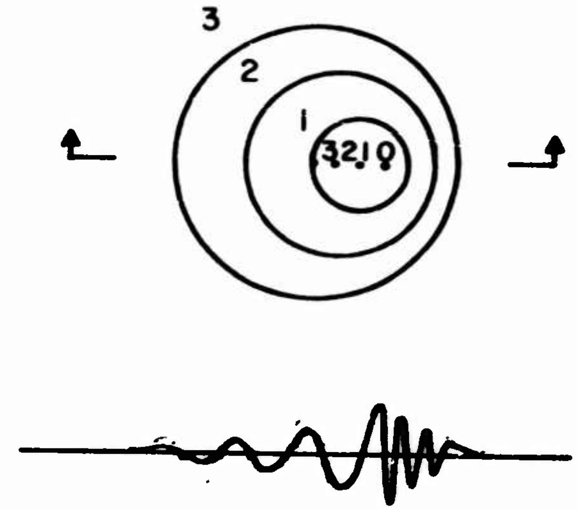


FIGURE 1.2c

stricted to the sector behind the advancing wave front. No disturbance would be experienced at a point until this wave front arrives.

Figure 1.3c is the corresponding diagramatic representation. Note how wave fronts of different age intersect and several intersections can occur close together in the neighborhood of the exterior envelope. This serves to concentrate the wave energy into that region.

The above mechanism is similar to, but not identical with that which occurs as the result of the supersonic flight of a solid body. Thus, the solid body is not analogous to a pulsating source, but rather to a distribution of steady sources and sinks (sinks are sources of negative strength). The positive source strengths would correspond to the amount and velocity of fluid displaced outward by the thickness of the moving body, and the negative sources to the return of the fluid back to the original position at the tail of the body. The abrupt change in direction of the flow at the nose corresponds to a large source which produces a shock wave attached to the nose. At the tail the inward flowing fluid is suddenly straightened and another shock called the tail wave is produced. Since the sources are steady in time, the wavelets producing the wave fronts "run together" and produce smooth fronted waves which are straight lines as in photograph 1.3b (and in the case of a ship's bow wave) and conical surfaces in the case of a solid body moving through the air, Figure 1.4. This diagram indicates that there is no disturbance anywhere except in the region between the nose and tail wave fronts or shocks. Between the shocks, the waves are weak and are called Mach waves. The foregoing is true in air, but only imperfectly observed behind the wave fronts of a ship, because water waves generally (except under controlled laboratory conditions) travel with a variety of speeds, resulting in more complex fields than in air.

All of the diagrams presented above are similar in

FIGURE 1.3a

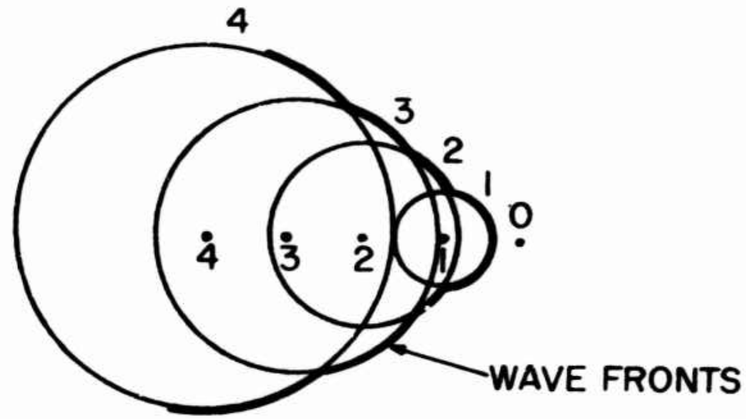


FIGURE 1.3c

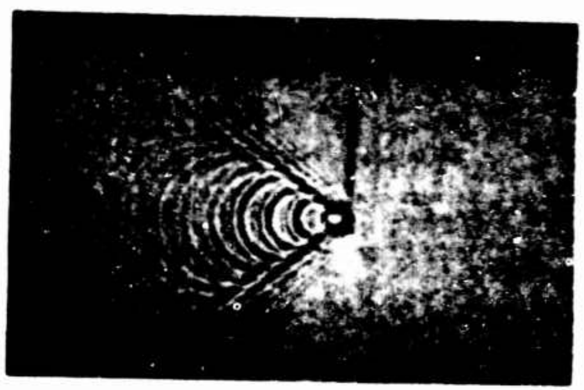


FIGURE 1.3b RIPPLES FROM FAST (SUPERSONIC) SOURCE

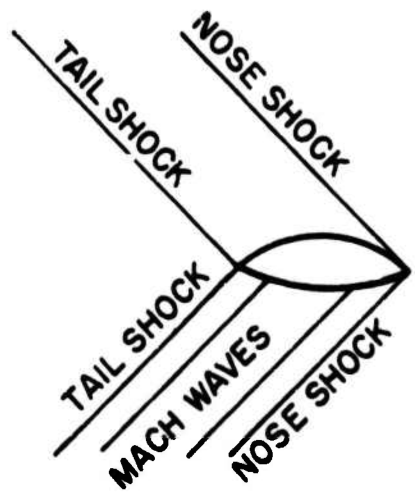


FIGURE 1.4
PROPAGATION OF SHOCKS, WEAK WAVES AND RAYS FROM SUPERSONIC BODY

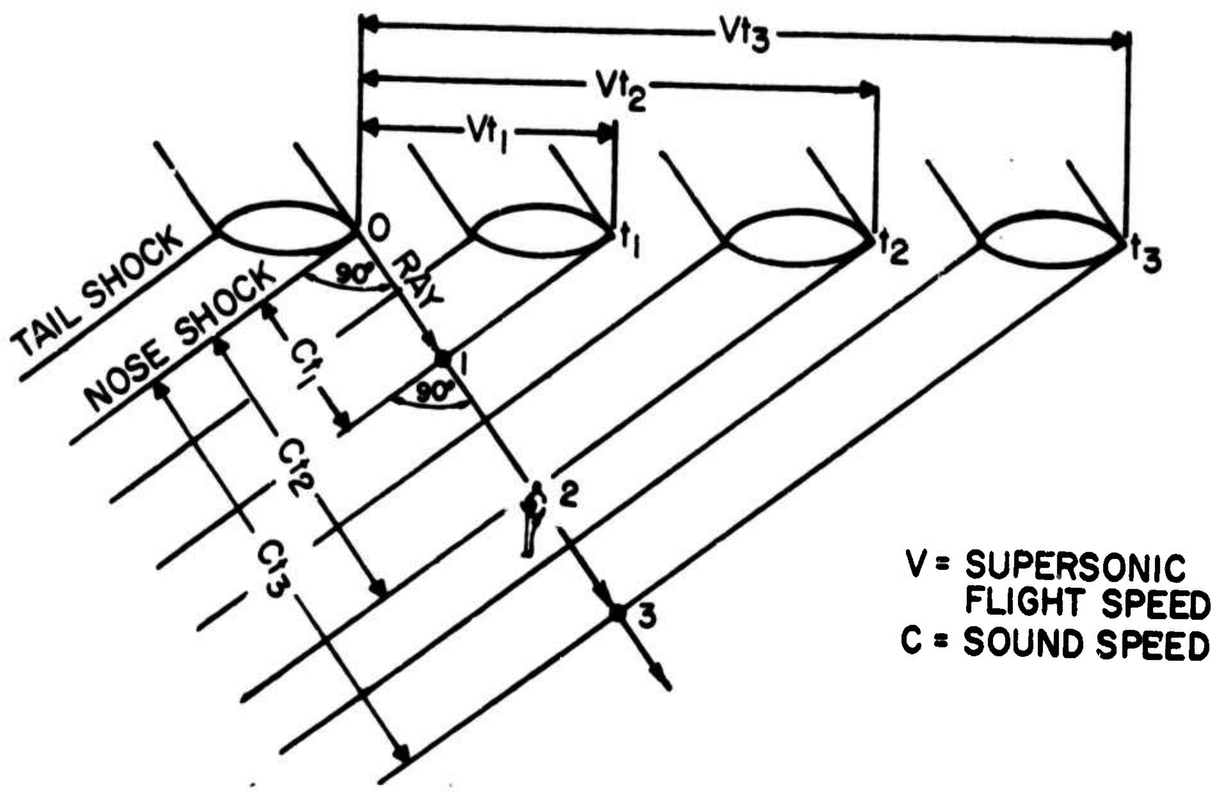


FIGURE 1.5
SUCCESSIVE POSITIONS OF AIRCRAFT, SHOCKS AND RAY AS SEEN BY STATIONARY OBSERVER

the respect that they present the "current" position of the wavelets and wave fronts corresponding to the "current" location of the sources which produces those wavelets and fronts. It is also useful to watch the wave fronts move in time relative to an observer who is fixed in space.

Figure 1.5 shows four successive positions of a supersonically moving body at times $t=0$, t_1, t_2, t_3 and at distances 0, Vt_1, Vt_2, Vt_3. Also shown are the distances 0, ct_1, ct_2 and ct_3 traveled by the bow wave disturbance in the same times. The portion of the wave front which contacts the observer at time t_2 is the same as that which originated on the nose of the body at time 0. This disturbance had traveled down along the ray (drawn on the diagram to emphasize its perpendicularity with the wave front). It can be seen from the diagram that a short time later, the disturbance from the tail of the body will reach the observer and it will travel down the same ray (any other ray will not strike the same observer). This allows us to picture the energy transmission from the moving source to the observer as occurring in a kind of a pipeline or ray tube with a piston-like source at the upper end of the pipeline. The piston can be considered to be the surface of the moving body itself, which forces air into and out of the pipeline. The cross-sectional area of the piston (which governs the total volume of airflow in the ray tube) is found to be the sum of all the cross-sectional areas of the body which at a given instant of time are perpendicular to the ray tube (parallel to the wave fronts) and, therefore, can contribute simultaneously into the ray tube.

In order to clarify this concept somewhat, we consider in flight an enlarged version of Figure 1.5 showing a body with a wing and a bump on the lower surface. It will be seen that the source contribution in the neighborhood of a point P_1 in the body has just begun at time t_1 to feed its influence into the ray tube which will hit the observer. This

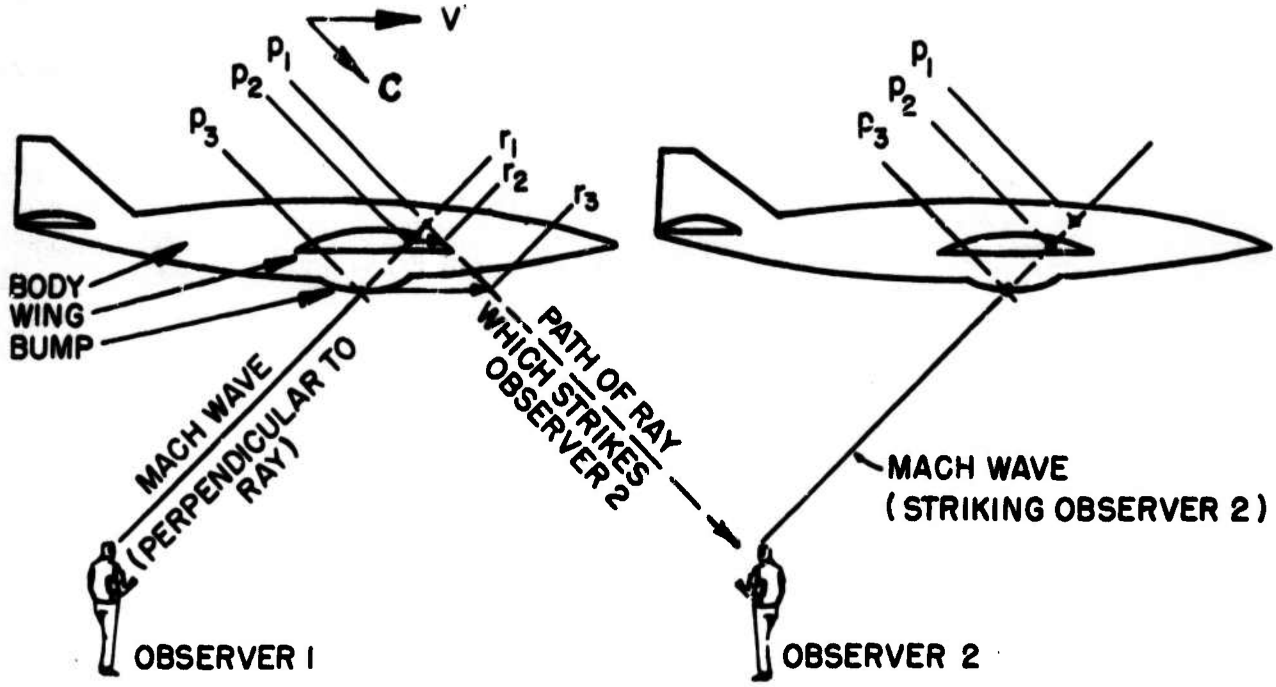


FIGURE 1.6
COALESCENCE OF SIGNALS FROM VARIOUS
SOURCES ALONG COMMON MACH WAVE

influence will travel down the ray tube with the speed of sound so that at time t_2 it reaches point r_2 on the ray. This is also the time required for an area element P_2 on the wing to be transported at the vehicle speed V (greater than C) from its original position to the same point r_2 on the ray; at which time it adds its influence into the ray tube. Similarly, P_3 travels farther, but at supersonic speed it joins the other two disturbances at the point r_3 of the ray. The orientation that the Mach wave (or Mach cone) takes relative to the moving body and its dependence on the ratio of vehicle speed to sound speed assures that this seeming succession of coincidences does indeed occur. Thus, when the disturbance finally reaches the observer at the end of the ray tube, the Mach wave will also be seen to cross the observer. If the observer should then look up at the vehicle in a direction along the Mach wave, his visual plane will intersect all the area elements responsible for the disturbance he is hearing at that instant.

This phenomenon has been the basis of the "hour-glass" fuselage shapes which vary and reduce the fuselage area to compensate for the locally greater wing cross-section and is called the "supersonic area rule" (to be discussed in the next section). It is also the basis of sonic boom minimization techniques discussed in section 4 of this report.

A very important phenomenon takes place within the ray tube, <u>after</u> leaving the vehicle, whereby the portions of the wave having higher than ambient pressure travel faster than those of lower pressure. This effect is unimportant at low disturbance levels and across small distances, but is very significant in the context of the sonic boom situation since it accounts for important changes in the wave shape over the long distances which apply. A discussion of this effect will be found in the section on Propagation.

2. Generation

The spectacular rise in maximum speed of aircraft in the last three decades has caused most of us to forget that certain branches of supersonic aerodynamics are very old. In fact, the determination of the drag forces on bodies of revolution, such as gunnery projectiles, has as long a history as almost any branch of aerodynamics. In particular, drag coefficients for spherical projectiles were determined at speeds of up to Mach 2 (twice the speed of sound) as long ago as 1742. Ernst Mach (1836-1916), a professor of physics in Vienna, and probably better known for his contributions to philosophy, made both mathematical and experimental studies of supersonic flow, his original paper having been published in 1887. Subsequent studies by Prandtl (1907), Meyer (1908) and Ackeret (1925) set the stage for the virtually explosive rate of progress in the thirties and forties.

Thus, the mechanism of sonic boom has been well understood for a long time. Procedures for calculating the pressure field around a supersonic body have also been available, and they were very well suited to calculating aerodynamic forces on the vehicle, but they were clumsy to use and increasingly inaccurate as distance away from the vehicle increased.

In 1947, Hayes (1) derived what was subsequently called the "supersonic area rule", which expressed the effective strength of sources of a given vehicle in terms of the area cross-sections cut out by the Mach wave, as previously discussed in connection with Figure 1.7. This made it possible to consider the real aircraft as an equivalent slender body of revolution (although one which would appear to have a different cross-sectional area distribution to an observer under the airplane than it would to the side of the airplane, Figure 2.1).

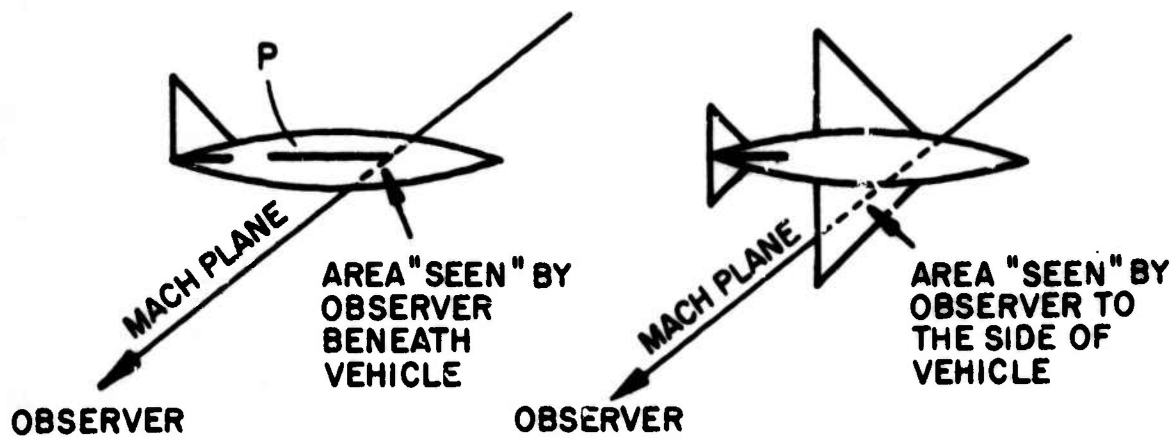


FIGURE 2.1
EFFECTIVE CROSS-SECTIONAL AREA OF AIRCRAFT AS SEEN BY OBSERVERS BENEATH AND TO SIDE OF VEHICLE

In 1952, Whitham (2) derived a mathematical formulation which, starting with the equivalent slender body concept due to Hayes, permitted the calculation of the entire pressure field except for the region close to the body. This formulation made it possible to calculate the pressure field due to the cross-sectional area distribution (the volume per unit length distribution) of real aircraft configurations. (In the sonic boom literature this cross-sectional area effect is often termed the volume distribution effect.)

In the above discussions only the volume effect of the supersonic bodies was considered as contributing to the distant disturbance field. This volume effect is not, however, the only possible source of disturbance. A thin wing flying at an angle of attack (presenting a lifting surface to the airstream) will also create a pressure field in the neighbor-

hood of the surface, which propagates away in the same way as does the volume source. The first treatment of the effects of the lift distribution over the wings and fuselage of an aircraft was presented in 1955 by Busemann (3). In 1958 Walkden (4) extended Whitham's formulation to account for the effects of the wing lift distribution and for the interference effects between the wing and fuselage. These additional effects were presented in such a way that they could be handled easily like an equivalent volume distribution. In 1960 Morris (5) performed a theoretical investigation to compare the relative importance of lift and volume effects. This work showed that lift effects were unimportant at low altitudes, but that for large airplanes at high altitudes the lift became dominant.

During the years 1959-1964 a great deal of experimental work was done in wind tunnels and in flight tests to investigate the validity of the basic theories. These tests demonstrated that the Whitham-Walkden-Hayes theory gave good estimates of the maximum sonic boom intensity in both the near field and far field.

No attempts were made prior to 1964 to calculate the details of the pressure field other than the peak values because of the difficulty of this calculation in the case of a practical airplane configuration. In 1964 H.W. Carlson (6) and the Boeing Company (7) developed digital computer methods and programs which used the supersonic area rule to calculate a realistic source distribution and they applied it to the computation of the detailed distant pressure field. In 1965 Middleton and Carlson (8) extended the numerical computation to the more difficult near field pressure signatures.

In subsequent years, investigations into the more extreme and complex conditions, such as high Mach number and extreme near field, were continued and more precise formulations of Whitham's theory were studied. These investigations are generally not yet at a stage where they can be easily used

in engineering applications.

Conclusions

1. Whitham's theory, together with the supersonic area rule, still forms the basis of sonic boom generation theory for Mach numbers less than about 2.5.

2. Several promising theories have been developed for the high supersonic and hypersonic Mach number regimes where Whitham's theory ceases to be valid. However, these theories have not yet been verified experimentally.

3. Propagation

In the previous section the materials discussed were concerned primarily with the strengths of the sources that generate the sonic boom disturbance. In this section the attention will be on what happens to the disturbance as it moves down the ray tube. The most important occurrences during this propagation include:

1. Change of shape of the pressure disturbance wave because of the greater wave speed of the higher pressure portions of the wave as compared to the slower.

2. Change of direction of the acoustic energy ray tubes due to horizontal winds and to temperature layering of the atmosphere with altitude.

3. Random distortion effects on the sonic boom wave shape due to passage of the waves through regions of high atmospheric turbulence.

4. Other propagation effects due to focusing also occur and have strong effects.

Change of Shape and Steepening

The essence of the mechanism underlying the first item above can be conveyed by reference to the equivalent water wave phenomenon, which is observed at the seashore. There it will be seen how a wave at some distance from the shore is generally smooth and symmetrical, Figure 3.1a. As it gets closer to the shore (b), the front gets steeper and the rest gets flatter. This change of shape occurs because the wave propagation speed of the deeper portions of the wave is greater than that of the shallower portions. Therefore, the wave crest overtakes the wave trough until the wave front becomes almost vertical. As the crest con-

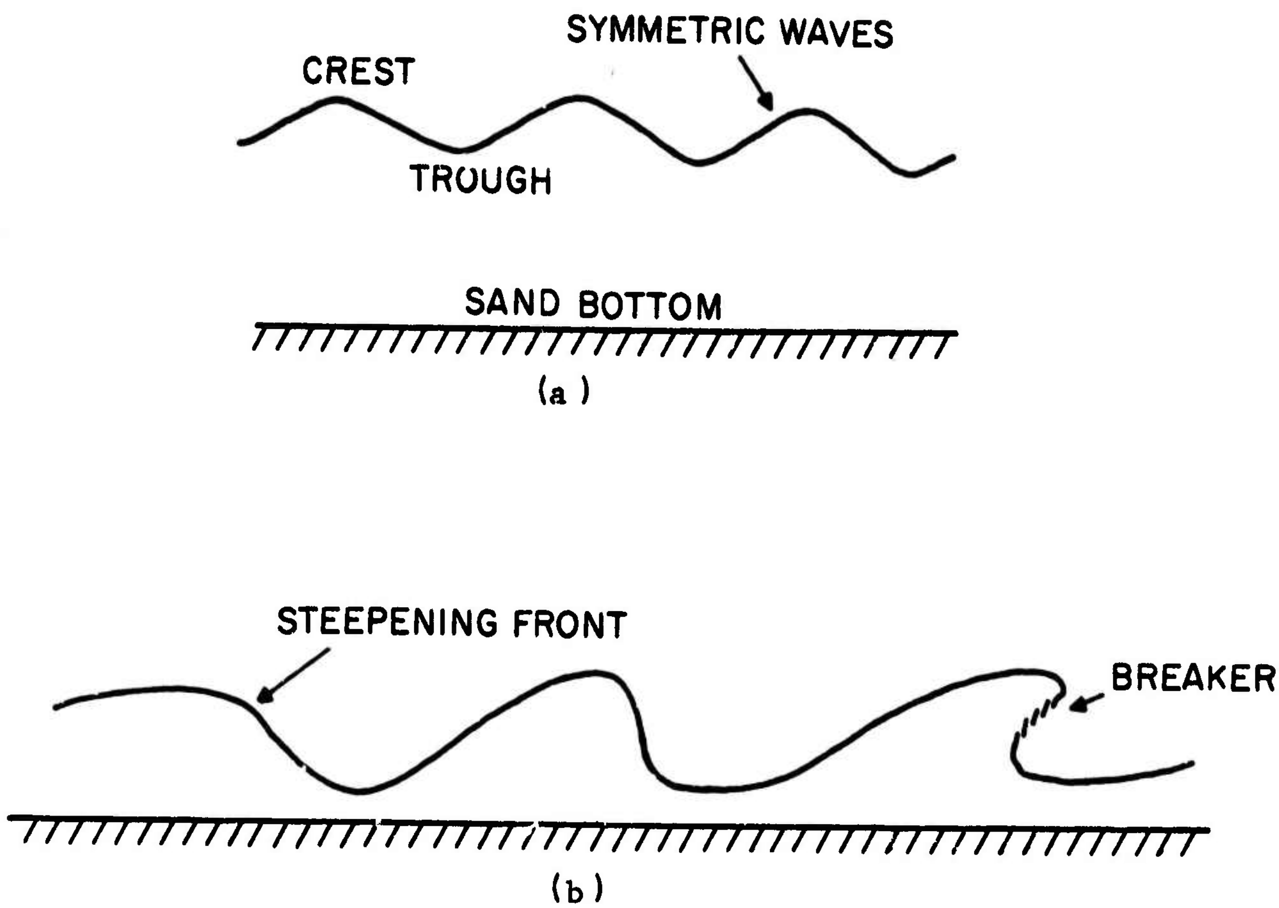


FIGURE 3.1
DEVELOPMENT OF BREAKERS IN WATER WAVES

tinues to outstrip the trough, it overreaches and a breaker is generated.

This is almost exactly the phenomenon in sonic boom. The wave speed of the more compressed regions is again greater than that in the under compressed regions. This happens because the compressed regions are slightly warmer than the expanded regions (which are slightly cooler). A basic fact of the physics of air is that the speed of sound depends only on the temperature and increases as the square root of the absolute temperature.

$$\text{sound speed} \simeq \sqrt{\text{absolute temperature}}$$

Any initial disturbance shape, therefore, whether simple or complex, becomes deformed in this way, forms steepened crests which overtake the pressure troughs and ultimately simplifies down to the basic N-wave shape, Figure 3.2:

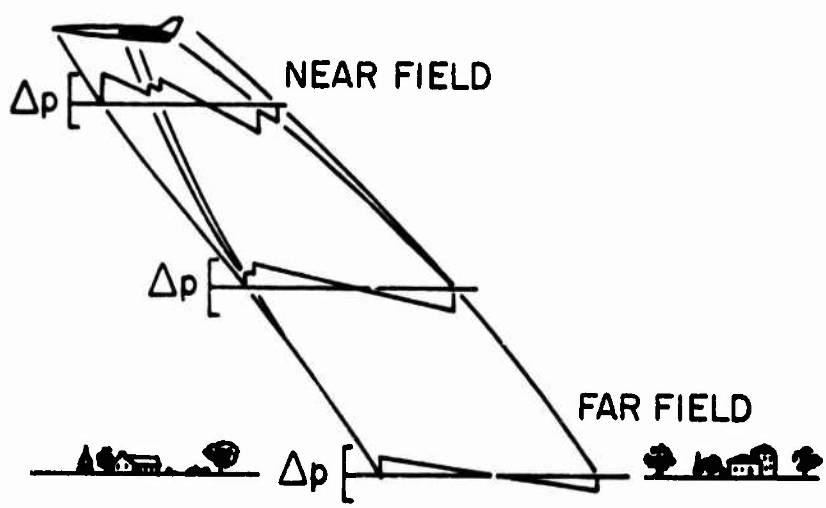


FIGURE 3.2
DEVELOPMENT OF N-WAVE FAR FIELD FROM
COMPLEX NEAR FIELD

The mechanism in air whereby the crests reach the troughs, operates along one dimension, not in two, as in the water wave. Therefore, the subsequent breaking phenomenon is different from, but still analogous to the events of Figure 3.1. Thus, according to the Whitham theory, if preliminary calculations show that the pressure crest which had started off as point 2 on the undistorted shape drawn in Figure 3.3 actually overtakes the initial point 1 and if the pressure trough 4 falls behind the end of the wave at 5, as in Figure 3.4a, then a corrected position of the wave front and wave rear must be constructed using a rule known as the "equal area rule". This rule has the effect of placing abrupt vertical fronts at positions such that the total area of the pressure wave remains the same. These fronts are placed at positions c and d in Figure 3.4a. The correctly redrawn pressure shape is then given in Figure 3.4b (with the uncorrected portions shown dotted in). Figure 3.5a shows the uncorrected disturbance at a still later time, with the corrected shape drawn in Figure 3.5b. It is seen from the successive diagrams that the length of the disturbance in the wave tube increases as a result of this "breaking" effect and consequently, the duration increases as the wave passes the observer. It is also seen from the diagrams that the wave gets to resemble more and more an N-wave, even though it may have looked quite different initially.

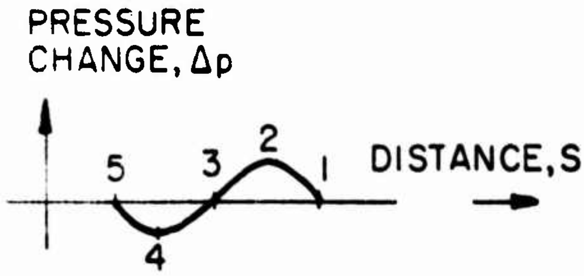
Atmospheric Layering Effects

The foregoing theory is due to Whitham (reference 2) and is one of the fundamental contributions to sonic boom theory. But, additional effects such as density, temperature and wind speeds are also very important in determining the impact of the sonic boom at the ground.

The underlying concepts governing the refraction of sound by a horizontal layering of wind speeds, were

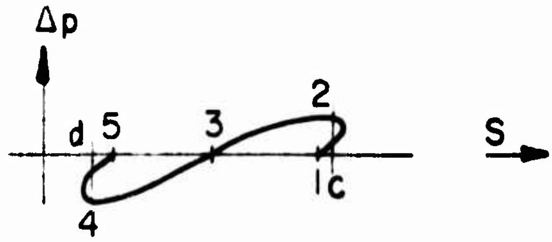
UNCORRECTED SHAPES

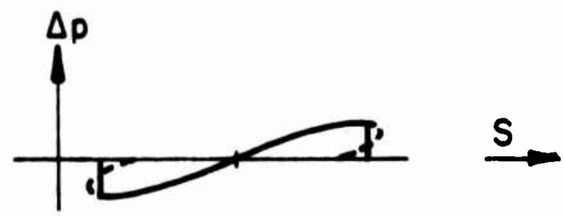
"ADJUSTED" SHAPES



UNDISTORTED SHAPE

FIGURE 3.3

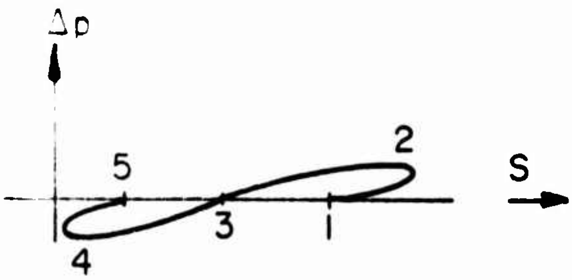




LATER SHAPE

FIGURE 3.4a

FIGURE 3.4b



STILL LATER SHAPE

FIGURE 3.5a

FIGURE 3.5b

developed as early as 1878 by Lord Rayleigh (9). However, the proper distinction between rays and wave fronts in a moving medium was not drawn in that work and corrected ray tracing equations for propagation in a single plane were derived by Barton in 1901 (reference 10). In 1912 Fujiwhara (reference 11) derived the correct equations in three dimensions, and in 1921 these were generalized by Milne (reference 12) to include the effect of sound speed variations along the wave path. An equation for conservation of sound wave energy flow down a ray tube was derived in 1946 by Blokhintzev (reference 13) which allowed the wave intensity to be calculated as a function of altitude (including wind and temperature effects).

The first effort to account for atmospheric stratification on sonic boom was made by Randall (14) in 1957. This was an approximate estimation of the effect of atmospheric pressure variation made by replacing the reference pressure in Whitham's results by the geometric mean $\sqrt{P_a P_g}$ of the pressure P_a at altitude and the pressure P_g on the ground. Improved procedures for correcting the magnitude of the ground shock due to a stratified atmosphere were developed in 1963 and 1964 (reference 15 and 16).

In 1968 a significant development was achieved in the computer program by Hayes, Haefeli and Kulsrud (reference 17) by means of which the pressure field can be computed for an airplane whose source strength distribution is known. The effect of atmospheric stratification, horizontal winds and airplane manouvers is taken into account by the program (the detailed position, orientation and speed of the manouvering airplane must therefore be input as a function of time). This is one of the most important papers written on the subject of sonic boom propagation and it represents the current state of the art of sonic boom theory.

A very important result of refraction of sound by

the atmospheric temperature layer is the bending of the sound away from the ground, so that under suitable conditions, the sound ray never intersects the ground. The optical analog of this phenomenon is often seen on highways on a sunny day, when the road surface seems to become replaced by a silvery mirror. This phenomenon occurs because light travels slightly faster in the hotter less dense air layer near the road surface than it does in the cooler air above the layer, Figure 3.6.

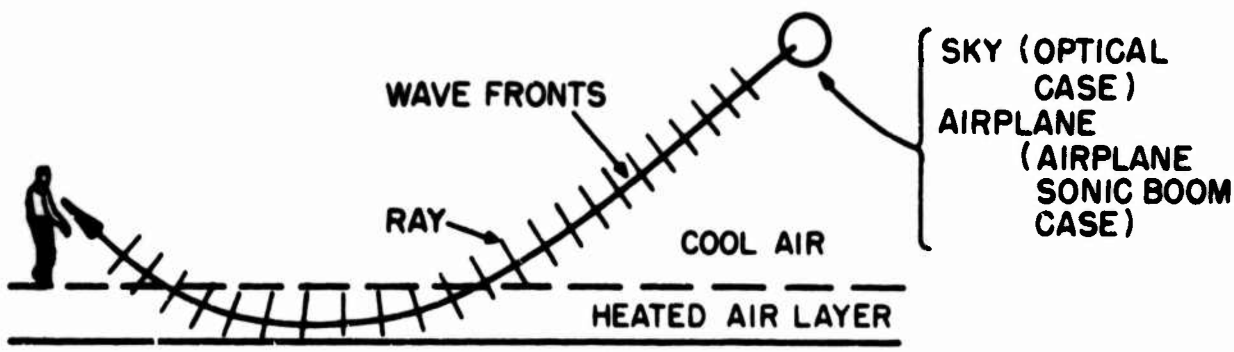


FIGURE 3.6
REFRACTION OF RAY BY HEATED AIR LAYER

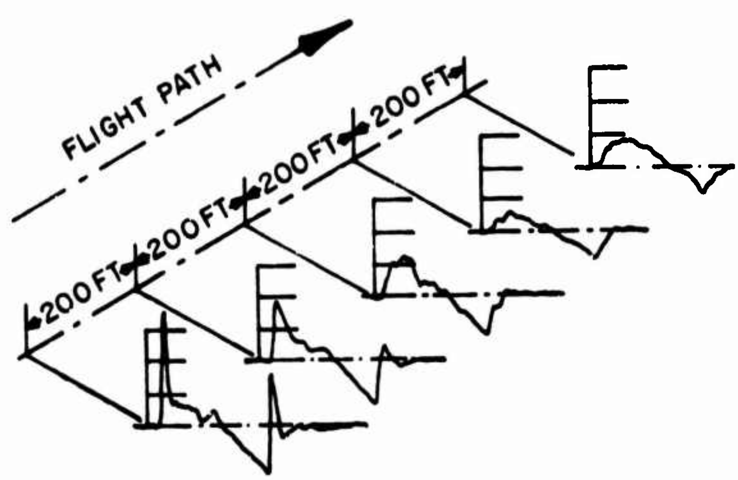
The observer then sees the equivalent of a reflection of the sky as he sights back down along the light ray that reaches him. Exactly the same mechanism is at work in the acoustic sense because the speed of sound is greater in warmer air near sea level than in the colder air at altitude. The bending of the sound ray takes place more gradually, however, as the average sound speed changes from 969 feet per second at 40,000 feet altitude to 1,120 feet per second at sea level

(the average sound speed at higher elevations between 40,000 feet and 70,000 feet is almost constant).

This atmospheric thermal refraction phenomenon has suggested a flight procedure which avoids sonic boom on the ground known as "threshold" Mach number operation. This concept is discussed in section 8 of this report.

Distortion of the Wave Shape by Turbulence

Flight test experiments carried out by Maglieri, Hubbard, Parrott (18, 19, 20, 21 and 22) and others during the years 1964-1968 verified many critical aspects of sonic boom theory. They also found that the random structure of the atmosphere near the ground has a significant effect on the shape of the sonic boom signature, resulting in "spiked" as well as "rounded" wave forms. Thus, successive wave shapes measured along the ground track of an airplane in steady flight by a series of identical microphones are sketched in Figure 3.7.



MEASURED SONIC-BOOM PRESSURE SIGNATURES AT SEVERAL POINTS ON THE GROUND TRACK OF A FIGHTER AIRCRAFT IN STEADY LEVEL FLIGHT AT A MACH NUMBER OF 1.5 AND AN ALTITUDE OF 29,000 FT.

FIGURE 3.7

A wide variation in wave shape occurs even over a distance on the ground of a few hundred feet. Substantially higher overpressures were associated with the sharply peaked waves and the lower value with the rounded-off waves. Figure 3.8 shows measurements recorded at a fixed station by several successive passes made first by an F-104 fighter and then by a B-58. Each pass was taken just a few minutes apart and the recordings illustrate the strong effects which occur.

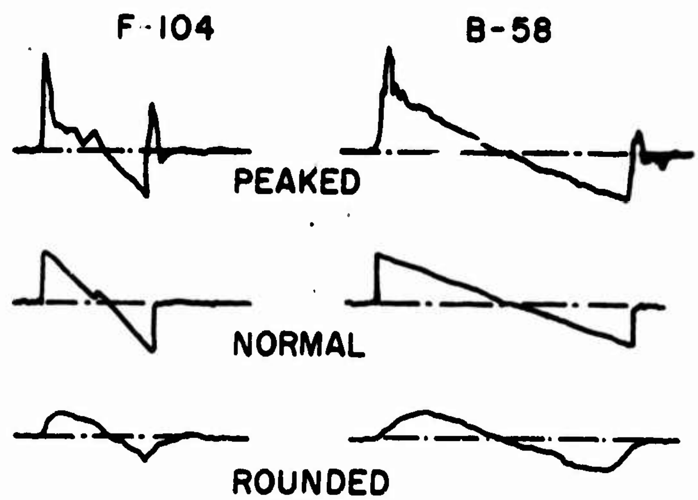


FIGURE 3.8
VARIATION IN SONIC-BOOM MEASURED SIGNATURES
FOR FIGHTER AND BOMBER AIRCRAFT

The most important theoretical studies of this phenomenon were carried out by Crow (reference 23) and by Pierce (reference 24). Each of these theories accounts reasonably well with many of the observed data and each is of a high order of mathematical quality. Both theories are plausible, although neither theory can be said to have been conclusively verified experimentally.

Focussing and Manouvers

Whenever rays of light cross, the crossing point will be the site of more energy than another ordinary point. If we think in terms of ray tubes, then we can recall the manner in which an ordinary magnifying glass can focus a ray tube of sunlight of the diameter of the glass, down to a spot which is a small fraction of that diameter. The result is an intense focussing of energy. If we use a lens of cylindrical shape, the resulting ray tube will converge down to a narrow line which is not as intense as the spot in the preceding example, but still much more intense than the original light beam.

A number of sonic boom phenomena produce focussing of acoustic energy very much in the manner of the cylindrical lens. One case of focussing in this way is produced by acoustic refraction due to temperature or wind stratification of the atmosphere. In fact, whenever we get total refraction at a surface such as in Figure 3.6, such focussing occurs. Redrawn in Figure 3.9, the diagram shows adjacent ray tubes which all start their downward path at angles determined essentially by the Mach cone orientation.

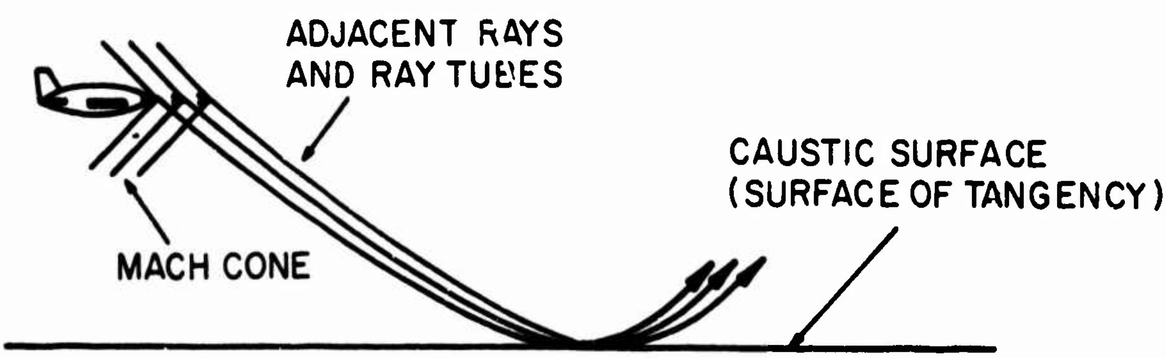


FIGURE 3.9
FOCUSSING BY REFRACTED RAY TUBES

As the ray tubes travel down, they may be refracted due to temperature and wind gradient effects, and if this refraction is strong enough, they curve back upward. The furthest distance downward reached by the rays is the surface of tangency (called the caustic surface). (Also see Figure 8.1 and discussion of Threshold Mach Number Operation.) It will be seen from the sketch that each ray tube must narrow down to zero cross-sectional area in the vicinity of the caustic surface and that the concentration of acoustic energy should therefore become infinitely great. A large increase in ray tube intensity does indeed take place, but is limited by complex (nonlinear) pressure alleviation mechanisms.

Similar focussing can be produced by manouvers of the airplane in flight. Thus, Figure 3.10 is a sketch of ray paths calculated by Lansing (25) for an accelerating aircraft in a shallow dive and pullout.

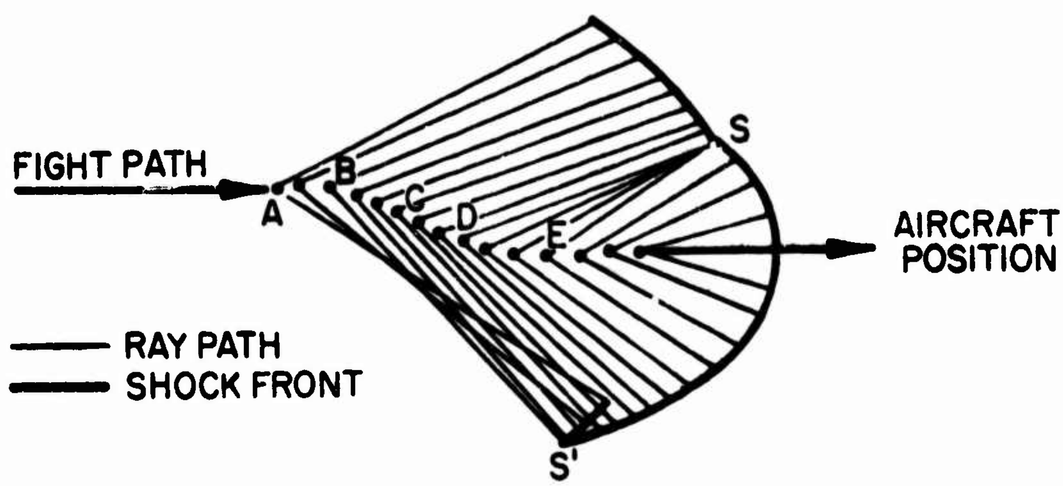


FIGURE 3.10
FOCUSSING BY MANOUVERING AIRPLANE

Two effects are illustrated by the above figure. The first is the focal point produced at the point S which concentrates all the energies radiated by the airplane between points D and E. The second effect is the cusp at S formed as the leading shock is folded back upon itself. The energy originating between points B and C of the flight path is then concentrated near that cusp. The regions of ray overlapping also concentrate the acoustic energy.

These problems of acoustic energy concentration were studied by Guiraud (reference 26), Hayes (reference 27), Seebass (reference 28), Wanner, Vallee, Vivier and Thery (reference 29) and extensive experimental studies are reported in reference 29 as well as by Haglund and Kane (reference 30). Several studies have used the computer program of reference 17 to make numerical studies of the effect of manouvers, e.g., Haefeli (reference 31) and Haglund and Kane (reference 32).

The possibility of large over-pressures in the range of 2 to 5 times normal have been found possible by Haglund and Kane under the special conditions of carefully controlled accelerated flight from Mach .95 to 1.2. Thus, it may be necessary to place constraints on manouvers at low supersonic Mach numbers. Other manouver effects such as pullups and pushovers are not ordinarily significant for large supersonic airplanes because of the limits in permissible operating conditions involving Mach number, altitude and structural load limits.

On smaller military aircraft, the greater inherent manouver flexibility result in the possibility of more extreme focussing effects. Thus, Wanner, et.al. (reference 29) analyzed the pressure signatures produced by various manouvers of Mirage III and Mirage IV aircraft and found that:

a. The boom intensity is multiplied by a factor

of 5 in the case of a focus and by the order of 9 for a superfocus.

b. The superfocus occurs over an area of approximately 300 foot radius, and the region of the focus is a narrow band of parabolic shape and of about 300 foot width.

Turbulent focussing effects generally do not result in overpressure factors of more than 2, and although these over-pressures add to the potential annoyance, they are in the form of very short duration spikes with relatively minor damage potential. Thermal focussing effects are important in connection with the so called "threshold Mach number operation" which are discussed in section 8.

4. Minimization

The concern that noise levels due to sonic boom were going to be a very difficult problem to overcome was expressed in 1955 by Adolf Busemann (reference 3):

> ". . . . an aerodynamicist by trade should not rely on the patience of the public and should make the reduction of the noise a special effort. The present investigation shows that most of the noise reduction is due to the natural non-linear spread of the pressure pulse under its own pressure, and very little additional help can be expected by those tricks which did so much to reduce the wave drag of the aircraft itself."

The phenomenon of wave drag as applied to supersonic vehicles had been discussed and explained by von Karman and Moore (reference 33) in 1932 and even earlier by Ackeret (reference 34). This wave drag was explained as corresponding to the expenditure of power to establish and transport the very extensive pressure field within the Mach cone of the vehicle. Von Karman compared it to the wave drag resisting the motion of a fast speedboat which could be alleviated by rising up on the hydrofoil step. Unfortunately, the airplane has no equivalent escape from supersonic wave drag.

Busemann further pointed out that the sonic boom noise and the wave drag were part and parcel of the same mechanism; reduction of the drag would also improve the noise. He pointed out that a vehicle could have a finite volume and yet have zero drag and noise. But this would have to be achieved by distributing the volume in a rather peculiar way, i.e., by building it like a body of revolution, with the outsides perfectly parallel to the flows and all the volume contours on the inside surface, Figure 4.1. In this

way all of the Mach waves could be "swallowed" and none radiated outside. Unfortunately, as soon as any lift is developed, the field radiates energy. Busemann also notes

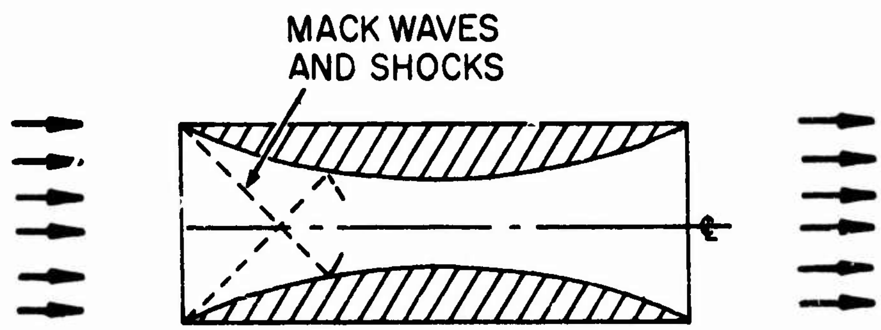


FIGURE 4.1
BUSEMANN BODY WHICH SWALLOWS SHOCKS

that since the airplane designer normally does his best to reduce wave drag, he is not going to have an easy time doing much better. Research in the years from 1955 to about 1965 was nearly all concentrated on techniques for minimizing the sonic boom in the far field. Whitham's far-field (asymptotic) results showed that in order to minimize the bow shock overpressure the airplane should be as long as possible, the length over which lift is distributed should also be large, the weight should be as small as possible and it should fly as high as possible. Other studies (references 35 and 36) have shown that locating the engines as far to the rear as possible can reduce the sonic boom, and use of the "area rule" to contour the fuselage (resulting in a smooth equivalent area distribution) can lead to reductions in both sonic boom and wave drag. Unfortunately, aerodynamic and structural design considerations, vehicle usage and weight, limit the gains to be achieved by these and most other minimization concepts.

In order to gain some idea of the limits of improvement made possible by optimization, several studies were conducted of lower bounds of sonic boom effects, under various types of constraint conditions (e.g., fixed length, volume and weight). In the case where only far-field considerations are involved, the most important parameters of the sonic boom signatures are the shock over-pressure and the impulse (the maximum integrated momentum which can be transmitted by the boom to a responding structure). Jones (reference 37 and 38) made extensive investigations of the lower bound of the far-field bow shock over-pressure. He found that it was sometimes possible to arrange lift and volume distributions so that their effects would cancel each other. He also found that the optimum body for over-pressure calculated in this manner, was also optimum for far-field impulse.

The types of area distributions required for far-field lower bounds are quite blunt and, hence, do not represent a practical solution to minimization. However, they do provide an indication in the case of real designs, of nearness to the theoretical minimum.

Near-Field Considerations

In 1965 McLean published an important report (reference 39) which showed that under real flight conditions, the pressure fields created on the ground by many aircraft configurations could not be determined correctly using far-field estimation formulas. Calculations made with Whitham's general (non-asymptotic) formulation showed that the sonic boom signature for a 450,000 pound transport flying at a Mach number of 1.414 at an altitude of 44,000 feet, was far from asymptotic and was much weaker (by less than a half) than the asymptotic estimate. Wind tunnel model tests carried out under equivalent conditions resulted in very close correspondence with the calculations. This paper was the first to suggest that far-field theory may not be valid, even for

flight at high altitudes.

Also of importance in reassessing the applicability of far-field theory was the role of the very large atmospheric density variation through which the sonic boom must travel. This density increases by a factor of 10 between 50,000 feet and sea level. Busemann (reference 3) first noted this point and Hayes (reference 40) subsequently called attention to the implication that the shape of the sonic boom wave could be "frozen" into a shape of minimal annoyance potential and needs never develop the steep shock front.

The physical effect of the atmospheric density increase is to reduce the wave pressure amplitudes (a consequence of conservation of wave energy) which in turn slows or halts the steepening of the pressure wave fronts. In the water wave analogy, it would be comparable to waves which begin to steepen as they approach the shoreline, but are then somehow frozen in shape before reaching the critical breaking steepness.

Since 1965, most minimization studies have, therefore, been based upon sonic boom in the near-field where the characteristics of the pressure signature are still dependent upon the details of the airplane configuration. Thus, configuration modifications can be used to modify the ground pressure signature in a desired manner.

Configuration Effects

Unlike the asymptotic far-field sonic boom shape,

which is an N-wave, an endless variety of near-field signatures are possible. There are flat-topped signatures which minimize the maximum over-pressure by spreading it out, finite rise time signatures which have a small or negligible initial shock followed by a gradual rise to the maximum pressure, sawtooth signatures, and so on. Some of these may be less annoying or may produce a smaller structural response. Procedures are available (Barger, reference 41) to calculate back from a given signature to the body shape required to produce it.

All of the studies note in common the advantage of making the airplane body as long as possible in order to delay the wave steepening process and forestall the development of shocks. Ferri and Ting (reference 42) were among the first to suggest that a secondary lifting wing in a biplane configuration, Figure 4.2, could be used, whereby the required length of the airplane is reduced in a tradeoff with the height of the secondary surface above the primary. In accordance with the ideas mentioned in connection with Figure 1.7, the observer on the ground experiences disturbances initiated by the Mach wave 1 (of Figure 4.2) and ending with the passage of Mach wave 3. If the wing surfaces were all in one plane, the same pressure distrigution would be produced by an airplane of equivalent length, L_{eq}, which is considerably larger than the fuselage length, L_{fus}. Ferri has designed an airplane configuration (reference 43) making use of near-field effects to reduce over-pressures to about 1 psf. Wind tunnel tests conducted with a model of this configuration verified the calculations.

Just as in the case of far-field signatures, it is important to know the minimum attainable shock strengths and over-pressures when near-field conditions exist. The study of the near-field lower bounds made by Seebass and George (reference 44) was one of the most extensive of this type. They found that the lower bound on shock strength

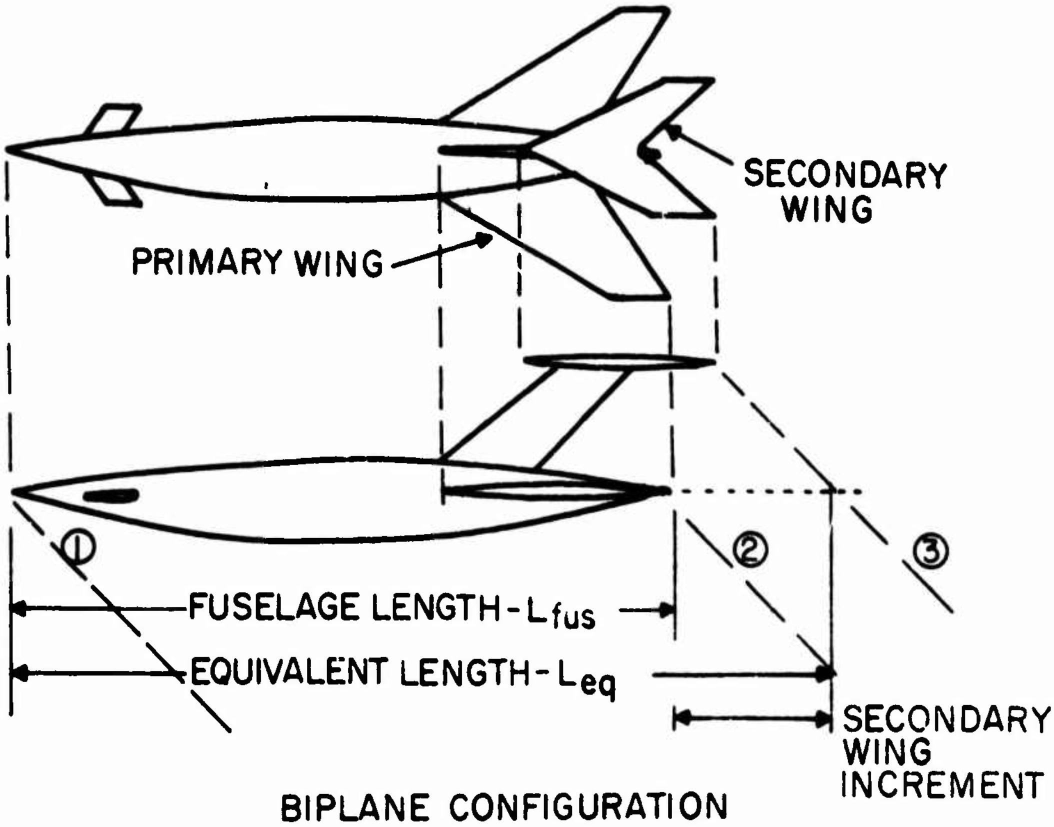


FIGURE 4.2
DIAGRAM SHOWING INCREASE IN EFFECTIVE LENGTH - L_{eq} - OF AIRCRAFT BY RAISING SECONDARY WING

could be reduced to about 50% of the Jones far-field results for a typical supersonic transport configuration. However, the minimum near-field impulse was of the order of 30 to 50% <u>higher</u> than the Jones results. They also found that for an airplane weighing 600,000 pounds, flying at M=2.7 at an altitude of 60,000 feet, lower bound overpressures are less

than 1 psf for airplane lengths greater than 300 feet.

Unconventional Schemes

A good deal of discussion (often heated) has appeared in the literature regarding various sonic boom minimization schemes which involve such things as adding (or subtracting) mass or heat to (or from) the flow surrounding the airplane. Among the interesting mechanisms is that of Cahn and Andrew 1968 (reference 45) which preposed the application of a very intense electrostatic field to the forward portion of the supersonic airplane. It was anticipated that a smoother parting of the incoming airflow would be produced by the charge distribution, resulting in a weaker nose shock discontinuity. Some experiments were carried out in liquid media which were interpreted as confirming the concept. A paper by Cheng and Goldburg (reference 46) was then presented in January 1969 criticizing the soundness of the concept and noting that a 10% reduction in sonic boom intensity would require on the order of thousands of megawatts of electric power and an enormous weight of machinery to generate the electric field intensities called for.

Another concept by Rethorst, Alperin, Behrens and Fujita (references 47 and 48) sought to eliminate shocks due to lift by guiding the engine exhaust flows along the aircraft lifting surfaces to produce a (presumably) better lift distribution. Wind tunnel experiments were performed which when extrapolated into the far-field were interpreted as implying a 30% reduction of shock strength intensity. The same data was reviewed by Weeks, (reference 49) who concluded that the analytical claims made were not completely valid and when corrected would result under the most favorable conditions in an attenuation of shock strength not to exceed 9%.

In 1970 Batdorf presented a paper at an AIAA meet-

ing in which an analysis of the possibility of modifying sonic boom characteristics by thermal means was discussed. The purpose of the heat was to cause expansion of the air and thereby to change the airstream path around the airplane, producing a "phantom body" with desired shape. In particular, this might be the means of creating a very long phantom body thereby implementing the generation of finite rise time pressure fields ("bangless" booms).

Two methods of adding this heat to the flow were investigated — a "thermal spike" and a "thermal keel". The thermal spike concept is based on the addition of heat ahead of the airplane by such means as a laser beam. The thermal keel is based on the concept of heat addition by an auxiliary fuel source located below the airplane and to the front or above the airplane and to the rear. The source distribution could thereby generate a body of larger equivalent length as in Figure 4.2.

In a report prepared in 1971 by Lipfert (reference 50) a unified study was made of all identifiable means of altering the flow near an airplane to examine the technical feasibility and practicability of achieving the desired flow field modifications and to assess the penalties incurred. The reduction and expression of any mass, momentum or heat addition scheme in terms of an effective area distribution was carried out and many mechanisms considered including free combustion, boundary layer mass addition, force fields and laser generated heat fields. It was concluded that use of air stream alteration schemes to eliminate or substantially reduce the shock would require gross weight penalties on the order of 100% of the baseline aircraft weight. On the other hand it might be feasible to fly two aircraft "in formation" in such a way as to create favorable signature modification.

Conclusions

The following are some general conclusions concerning the present state of the art of sonic boom minimization efforts:

1. Modification of sonic boom signatures in the near-field offer the best possibility of achieving significant reductions.

2. Unconventional schemes involving the addition of mass or heat to the flow or the creation of a "phantom forebody" do not appear to be practical.

3. In order to produce a finite-rise-time pressure signature, the airplane should be as long as possible, it should fly at a low altitude and it should fly at a low supersonic Mach number.

4. It has been demonstrated both theoretically and experimentally that a domestic SST configuration designed to produce a near-field signature can generate front shock strengths on the order of 1 psf at cruise altitude. However, the commercial viability of such a configuration remains to be determined.

5. Substantial improvements in the area of aerodynamic efficiency, propulsion efficiency or structural weight would have a direct beneficial effect on sonic boom minimization.

5. Human Response and Social Criteria

The previous sections have been concerned with some of the purely physical and engineering aspects of sonic boom phenomena. One of the primary reasons for concern over sonic boom has been, however, the impact of sonic boom on human health, comfort and safety, structural safety of buildings and on both wild and domestic animal life. Each of the above areas has been extensively investigated. In this section, some of the principal results of studies of human reactions will be discussed.

Field Studies

Numerous field studies have been conducted in an effort to better understand community response to sonic booms. Most of these studies have used actual overflights of supersonic aircraft. The three most extensive investigations of this type were those conducted in Oklahoma City, in St. Louis and at Edwards Air Force Base (California).

St. Louis

The population of St. Louis, Missouri, was repeatedly exposed to sonic booms in a range of over-pressures up to about 3 psf during a seven month period in late 1961 and early 1962 (reference 51). A total of 76 flights were made by B-58 and F106 aircraft. In order to assess community response to these booms, a series of personal interviews were conducted. The following conclusions were reached:

1. After 66 supersonic flights, about 90% of those contacted experienced some interferences (speech, activities, etc.) as a result of sonic booms, about 35% were annoyed by them, less than 10% had contemplated complaint action and a fraction of 1% had actually filed a formal complaint.

2. The cumulative total of complaints recorded was approximately proportional to the number of supersonic missions. A large percentage of recorded complaints made some mention of building damage. There were no direct adverse physiological effects.

Oklahoma City

A total of 1,253 sonic booms were generated in the vicinity of Oklahoma City, Oklahoma, over a period of six months from February to July 1964 (reference 52). The average intensity on the flight track was 1.13 psf during the first 11 weeks, 1.23 psf during the next 8 weeks and 1.60 psf during the final seven weeks of the program. The booms were generated by F104, F106, F101B and B-58 aircraft.

Almost 3,000 adults representing a scientifically selected cross section of local residents were personally interviewed three times during the six month period to determine their reactions to the sonic booms. In addition, careful records were kept of all complaints received by the local Federal Aviation Agency representatives. The following conclusions were reached:

1. Almost all residents (94%) reported that sonic booms caused house rattles and vibrations. Smaller percentages reported interference with living activities: being startled 38%; interruptions of sleep 18%; of rest 17%; of conversation 14%; of radio and television 9%. Persons favorably inclined towards the goals of the experiment were much less disturbed by sonic boom than persons unfavorably inclined or afraid of aircraft.

2. Annoyance increased as the duration of the program and the exposure intensities increased (37% after first interview to 56% after the third). Most of the increased annoyance was attributed to the increased sonic boom over-pressure.

3. Reports of structural damage increased from 20% during first and second interview to 25% after third interview. During the six month test, 38% overall felt they had been damaged, with plaster cracks as the most frequent complaint.

4. Only 22% of all residents felt like complaining about the sonic booms at the end of the study and only 5% actually did. Those with the most favorable attitudes toward booms reported that only 3% ever felt like complaining about the booms and only 2% actually did. In contrast, 37% of the most hostile group felt like complaining and 12% actually did.

5. The vast majority of residents felt they could learn to live with sonic booms. Over 90% felt they could accept eight booms per day indefinitely on the first interview, and 73% felt this way at the end of the six month period. About 92% of persons with the most favorable views said they could accept the booms at the end of the study compared to 57% of the most hostile group. Even 40% of the persons who actually complained to the FAA said they could probably learn to live with the booms.

6. Respondents who had personal or family connections with the aviation industry reported the same reactions as persons with no aviation connections.

7. Reactions of urban and rural residents to sonic booms were essentially the same.

8. Persons who actually complained to the FAA were the most intensely annoyed and most hostile toward the SST. They were not chronic gripers and liked their areas as well as non-complainers. They were equally sensitive to noise in general, but reported 3 to 4 times more sonic boom interference, four times more annoyance, 6 to 9 times more desire to complain and 3 times more damage by booms. They

less often believed in the importance of aviation in general, the necessity of the SST or the necessity of local booms. About 40% of the complainers, however, felt they could learn to live with eight sonic booms per day. Complainers were more often middle-aged females with older children and smaller families. They generally had more education and income and more often had ties with the aviation industry.

Some of the results of the foregoing study were summarized graphically in Figure 5.1, as taken from reference 53.

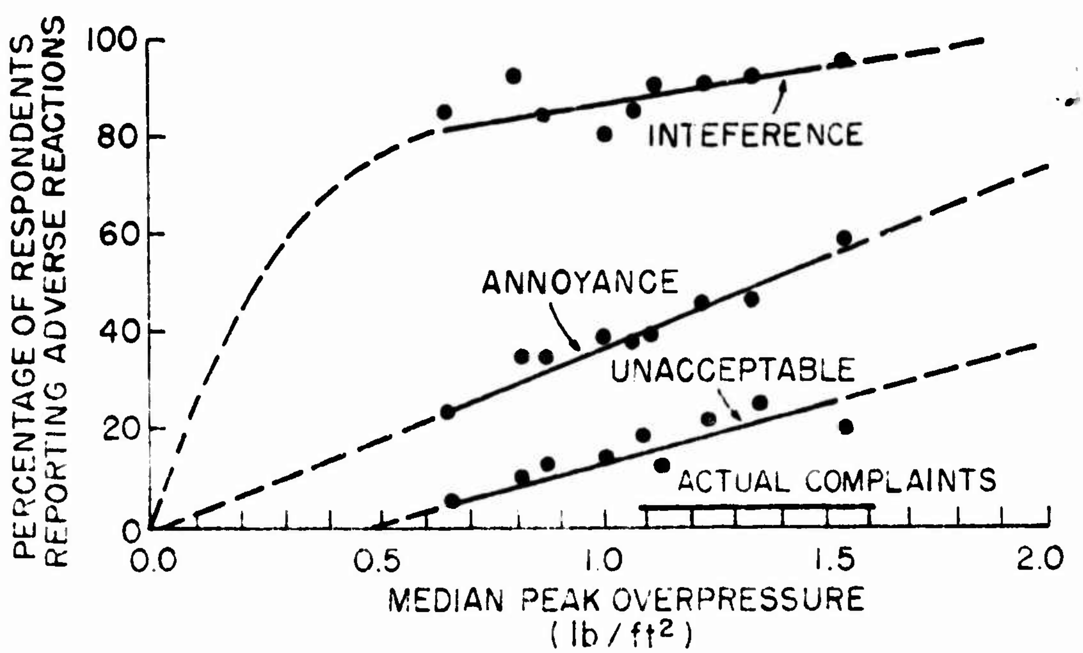


FIGURE 5.1
PERCENTAGE OF RESPONDENTS REPORTING VARIOUS TYPES OF ADVERSE REACTIONS TO SONIC BOOMS

Edwards Air Force Base

In 1967 a series of experiments were carried out at Edwards Air Force Base, California (reference 54) in which residents from the base and from neighboring communities of Fontana and Redlands occupied various indoor and outdoor test sites on the base and reported their psychological reactions to overflights by F104, B-58 and XB-70 aircraft, with overpressures in the 1.5-3.0 psf range. Subsonic overflights were made to serve as a comparison with the booms.

Conclusions

1. Indoors: Reactions to over-pressure of 1.69 psf were found less favorable by Fontana-Redlands subjects than by Edwards. Reactions ranging from less than "just acceptable" to "unacceptable" included 40% from Fontana-Redlands and 27% from Edwards. (Scale elements included acceptable, just acceptable and unacceptable.)

2. Outdoors: The above numbers become respectively 39% and 33%.

3. Averaged over all tests, outdoor listeners found booms and subsonic noise slightly less acceptable than indoor listeners. Also, judgment of outdoor listeners was more consistent.

4. Unacceptability rises more rapidly with sonic boom over-pressure than with subsonic noise pressure; about one and one-half times faster.

5. Age and sex were not found to be statistically significant parameters in the rating procedure.

6. The indications are that adaptation to sonic

boom repetition does take place.

Physiological Effects of Sonic Boom

One of the more extensive programs on physiological effect of sonic boom was carried out in Russia (reference 55). Recordings made of brain potentials (EEG), heart potentials (EKG), blood chemistry, arterial pressure, auditory acuity and visual response delay indicated short duration shifts for sonic boom intensities less than 1.72 psf. These shifts returned to normal in one to two minutes and the magnitudes of the shifts never exceeded the normal range of fluctuation for the subject. Booms less than 1.54 psf did not cause any measurable shift of physiological function.

Very intensive tests carried out at the University of Toronto Institute for Aerospace Studies (reference 56) exposed subjects to 50 sonic booms at the rate of 25 per minute at over-pressures of 2, 4 and 8 psf. The results indicated that sonic booms of up to 8 psf do not have a detrimental effect on human hearing or heart rate, but that peak over-pressures of 4 psf would be unacceptable to most people.

CHABA (the Committee on Hearing, Bioacoustics and Biomechanics of the National Academy of Science - National Research Council has published damage risk criteria recommending limits to peak impulsive noise level as a function of impulse duration for a nominal exposure of 100 impulses per day at normal incidence, (reference 57). The 1968 criterion was intended to protect 95% of the people according to an implied criterion of NIPTS (noise induced permanent threshold shoft) not exceeding 20 dB at 3 KHz or above after 20 years. A plot of maximum peak pressure versus impulse duration is presented in Figure 5.2. If 90% of the people were to be protected to a criterion of NIPTS not exceeding 5 dB at 4 KHz, it would be necessary to lower the

CHABA limits by 12 dB. This modified CHABA limit is shown in Figure 5.2 by hatched lines.

For impulse durations in the sonic boom range the modified limit is at 140 dB (4.17 psf). According to this criterion, sonic booms do not pose a threat to human health.

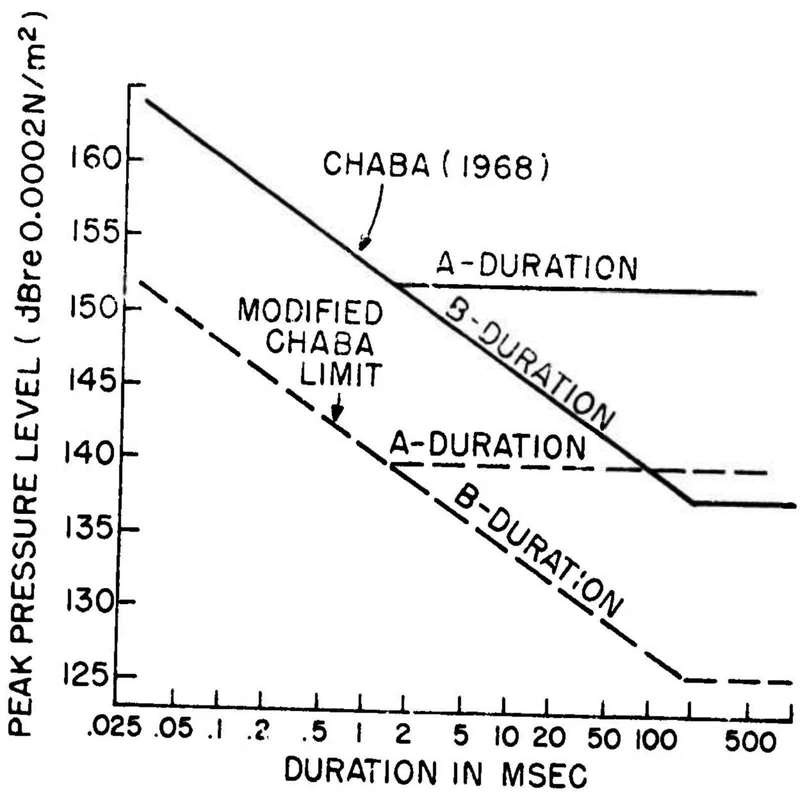


FIGURE 5.2
THE 1968 CHABA DAMAGE RISK CRITERION FOR IMPULSE NOISE EXPOSURE (SOLID) AND PROPOSED MODIFICATION (HATCHED)

Sleep Effects

The awakening effects of sonic booms has been studied in the laboratory primarily. Most of these investigations have been carried out at the Institute of Sound and Vibration Research at the University of Southampton (reference 58 and 59), the FAA Civil Aeromedical Institute (references 60 and 61) and the Stanford Research Institute (reference 62). The typical manner in which these experiments were carried out was to expose one or two subjects sleeping in a special simulation chamber resembling a typical bedroom to simulated sonic booms at various times during the night for a period of two to three weeks. In some cases only the number of awakenings was observed, while in others EEG measurements were made. The most significant findings of these various investigations were as follows:

1. Children 5 to 8 years of age are not affected by sonic booms during sleep.

2. Older subjects are more sensitive to sonic booms during sleep than are younger subjects.

3. Women are more sensitive than men to sonic booms during sleep.

4. Individuals may vary widely within an age group with respect to their relative sensitivity to sonic booms during sleep.

5. The frequency of behavioral awakening is a function of the intensity both in the case of sonic booms and in the case of subsonic jet flyover noise.

6. A significant trend has been noted between higher neuroticism scores and more frequent awakenings in response to sonic booms.

7. Awakening in response to sonic booms is more likely to occur during the latter part of the night.

8. No mood changes attributable to the occurrence of sonic booms during sleep have been found.

9. No residual effects on the performance of a complex task the morning after being exposed to sonic booms during sleep have been found.

10. No conclusive evidence has been obtained concerning adaptation to sonic boom exposure during sleep over an extended period of time.

11. An acceptable over-pressure for sonic booms generally compatible with undisturbed sleep cannot be established on the basis of information available currently.

Task Performance Effects

The review by Runyan and Kane (63 and 64) cites seven reports of studies (reference 65 to 71) which were carried out to investigate the effect of sonic boom on task performance. Some of the cited experiments involve purely physical skills, such as the visual and manual tracking of a target, whereas some also involve intellectual tasks, such as the recognition and counting of complex pattern pairs. Subjects were exposed to simulated or actual sonic booms of intensities varying from very low (0.2 psf) to very high (10 psf).

The response to the booms varied from subject to subject, but no statistically significant effects were noted for the tracking type tests at over-pressure levels below 2.5 psf. Intellectual performance was significantly interrupted, however, for periods lasting from 5 to 19 seconds after exposure. It was of interest to note that some subjects

(33 out of 108) gave more accurate results at 1.42 and 0.80 psf, although at a slightly lower rate.

It appears that from the available data sonic boom begins to significantly impair performance of a fast visual task at levels above 1.9 psf.

Loudness Studies

The "loudness" of a sound is the name given to the magnitude of the auditory response produced in the human auditory nerves by an externally incident fluctuating pressure field. The objective and subjective properties of loudness phenomena have been studied in great detail in connection with ordinary continuous sounds of pure tone as well as mixed tones. These studies have shown that the subjective magnitude of response depends in a fairly well defined manner on the sound pressure level and in a more complex manner on the frequency (tone) mixture and the duration of the sound. Procedures for establishing quantitative measures of loudness of a tone generally depend on comparisons made by large numbers of subjects between the tone and a reference tone having the single frequency of 1,000 Hz (middle of the human frequency sensitivity range). A compilation of many judgements made with the full range of tones and intensities of concern results in data that can be presented in the form of contours of equal loudness. The annoyance or perceived noise, experienced by people in response to continuous noise depends also on intensity duration and tonal content, but in a different degree than obtains for loudness. In addition, annoyance tends to depend on the meaning and environmental conditions under which the sound occurs. Paired comparison techniques are also used for the quantification of "perceived noisiness".

The study of the loudness and perceived noisiness of impulsive noise, including sonic boom, has tended to

follow both the methodology and conceptual approach developed in the study of continuous noise. Thus, a number of efforts to quantify loudness of a sonic boom have proceeded by finding the energy content of the recorded signal in each frequency band as in ordinary continuous noise (reference 72). Then the energy in each of these bands was adjusted to take into consideration the sensitivity of the human ear. The result could then be expressed in terms of units usually used for loudness, i.e., phons. At the same time, numerous studies have proceeded by comparing the loudness experienced by groups of auditors who were asked to listen to sonic booms and almost simultaneously to less complex sounds for which reasonable techniques of loudness representation or quantification already exists. These studies could then result in restricted statements like "a 1.69 psf sonic boom from a B-58 bomber heard outdoors sounds as loud as 110 PNdB noise from a subsonic jet airplane", or similar statements for different boom signatures or different listening conditions.

Efforts to devise numerical procedures of signature analysis which are consistent with the subjective estimates of the auditor experiments have resulted in about a half dozen methods (references 72, 73, 74, 75, 76 and 77) reflecting the several procedures for calculating loudness of steady sounds. These numerical procedures are of various orders of complexity. One of the simplest of them by May (reference 76) has been found to be as satisfactory in representing the available data as the more complicated procedures and this one can be stated in the form

$$L \text{ (phons)} = (\Delta p)_{dB} - \Delta t - 12$$

This formula shows that the loudness level (in units of phons) is directly related to the maximum overpressure (expressed in decibels) minus the rise time, Δt, in milliseconds (the time elapsed between the first detectable sonic boom pressure and the maximum value).

A similar simple sonic boom index by Higgins (reference 78) takes the same variables in •' ~~a~~lternative form:

$$\text{Sonic Boom Index} = K\frac{\Delta P}{t}$$

where ΔP is over-pressure, t is rise time and K is a convenient constant. This dependence on rise time is very important and has led researchers to seek ways of stretching the rise to the greatest extent possible. In fact, the name given to the kind of boom achieved by sufficient stretching of the rise time is called the "bangless boom", since it sounds more like rolling thunder than the sharp snap of a pistol shot.

Annoyance and Startle

The same types of tests as used for judging subjective loudness have also been used to assess annoyance (reference 79), but the problems encountered have been considerable. This annoyance depends on health, attitudes, m ods, motivation of the subject as well as on the stimulus. Test results can be influenced greatly by the wording of the directions to the subject and of the questionnaire. Annoyance is probably a composite of many factors including startle, apprehension, fear, interruption of communications, disruption of concentration, arousal from sleep, etc. It is cumulative and a person already annoyed by a frustrating job or unpleasant home situation is apt to respond violently to a disturbance which he would otherwise pass over lightly. It is believed that there does not exist at present, an annoyance assessment criterion for sonic boom which is reliable and has been adequately documented. It may be particularly hazardous to base any rules on comparisons with annoyance from subsonic aircraft.

Conclusions

1. The most frequently reported complaint in regard to overflights of supersonic aircraft is boom caused house rattles and vibrations.

2. Booms of similar intensity are rated slightly more unacceptable by listeners indoors.

3. In all of the tests conducted to date, there has been no evidence of direct personal injury resulting from sonic booms.

4. On the basis of experimental evidence to date, an acceptable over-pressure for sonic booms generally compatible with undisturbed sleep cannot be given.

5. Some experiments have shown a tendency for sonic boom exposure to degrade the performance of certain visual, steering and tracking tasks, while others have shown no effect on performance. The response is largely dependent upon the individual subject and the sonic boom over-pressure.

6. Structural Response

Three very large scale flight test programs together account for the great bulk of the instrumented and recorded data available for the description of structural response to overflight by supersonic aircraft. These include a 6 month program performed over Oklahoma City in 1964 (reference 80). The second program was conducted at White Sands, New Mexico in 1965 (reference 81) and the third investigation took place at Edwards Air Force Base in California in 1967 (reference 82). The Oklahoma City tests documented responses of eleven typical types of residential structures to controlled sonic booms at a frequency of 8 per day which were varied in over-pressure amplitude from zero to 3.5 psf. The program was followed by 13 additional weeks of inspection to determine the normal rate of deterioration of the structures in response to natural causes only. The increase in the rate of defect detection (per week of exposure) in the case of the boomed structures over that of the naturally deteriorating structures, varied by factors of one and one-half to almost three.

Not all types of defects behaved similarly. It was found, for example, that paint or plaster cracking occurred more readily than nail popping. Efforts to compare calculated with measured response motions demonstrated that the knowledge of the value of the maximum boom over-pressure was not by itself sufficient for making adequate predictions. (The implication was that the detailed time history of the pressure signal is also needed.)

The Edwards tests (reference 82) carried out at over-pressures ranging between 2 and 3 psf were designed to test the effect of sonic boom pressure-time relationships. For this reason, three different aircraft with boom durations ranging from one-tenth to three-tenths of a second (F104, B-58 and XB70) were flown over typical

wood frame houses as well as over a long span steel frame industrial building. The longer duration booms were found to affect a greater range of structural elements than the shorter signatures.

A sonic boom contains acoustic energies distributed over a wide frequency range, but with much of the energy propagated in waves with periods ranging from half to double the boom duration.

For this reason, the important oscillations of buildings and large windows (which generally tend to occur at vibration periods of 0.2 second or more) are more strongly affected by big aircraft sonic booms of 0.2 seconds or greater duration than by the short 0.1 second booms generated by small fighter planes. The peak normal wall displacements (usually called plate displacements) of typical walls were found to be on the order of 1/32" for sonic boom over-pressures of 2 psf. Maximum displacements in the plane of the wall (called racking displacements) were much smaller, by a factor of 20. Measured maximum displacements were found to be in good agreement with predictions calculated on the basis of the free field pressures (pressures measured in spaces free from reflecting or responding surfaces) and simplified mathematical models of the building structures. It was concluded from the test results and calculations that damage due to sonic booms of anticipated magnitudes was extremely unlikely.

The two test programs described above were carried out at over-pressure levels that emphasized magnitudes to be anticipated from commercial flight. The White Sands test program (reference 81) on the other hand included many tests at high pressures up to 20 psf, in an effort to induce and study cases of significant structural damage. F104 and B-58 aircraft were used to generate a total of 1,500 booms. Tests were carried out on 21 structures which were extensively

instrumented. Some additional insight was gained into the modes of deformation of large and small buildings, but no damage could be observed for over-pressures below 5 psf. Furthermore, there was no evidence of cumulative damage effects after a series of 860 successive flights at 5 psf.

Statistical Studies

The programs described above, as well as more reliably controlled laboratory and theoretical studies of structural response to sonic boom have resulted in the careful study of thousands of structures. Important as such an approach might be it did not give a complete projection of the effect of transcontinental flight programs involving several million man-booms per day, in which the range of possibilities of structural variation and repair condition are simply too great to study in detail.

In order to gather data and insight on the range of risk possibilities attending regular commercial supersonic overland flight, the flight program over Oklahoma City and additional flights over St. Louis (1961-1962) and Chicago (1965) were used to gather statistics on damage as reflected by the number of complaints and damage claims submitted by the public subsequent to supersonic overflight, the number of damage claims verified and paid and the dollar value of the claims paid. In general, most claims involved damage to glass and plaster and involved structures which were poorly constructed, poorly maintained and experiencing deterioration due to age. Claims of injury to people or animals were found to be rare and were of an indirect nature, such as persons claiming to be struck by falling objects or having been startled into injuring themselves.

A statistical study of glass breakage has recently (reference 83) been carried out using much of the available data which gives rational weight to the very large

number of independent factors contributing to breakage. These factors include such statistical inputs as window size likelihood, aircraft direction, boom duration and magnitude, glass condition (good condition or initial cracks). The study predicts a breakage rate for "healthy" glass exposed to 1 psf overflights, of one per million which is in agreement with test experience. However, for a mixed population of glass including some with initial cracks, the predicted breakage rate increased dramatically. Thus, inspections around Edwards Air Force Base indicated that of 100,000 glass sections, 0.6% were cracked. Use of this number in the statistical model indicated a breakage rate of 68 per million. The breakage rates would tend to double as the over-pressure is doubled. These conclusions are consistent with experience.

The study has the effect of pinpointing the importance of ordinary care in handling of glass and the rejection of faulty specimens and workmanship. It also has set forth a methodology which can be extended to other aspects of sonic boom damage estimation.

Terrain Effects

One of the sonic boom effects which was considered to be worthy of concern is the seismic wave induced on the surface of the earth by the sonic boom. The reason for this concern stems from the fact that under certain conditions of incident acoustic wave directionality and ground elasticity, a large interaction is possible with large ground vibrations. Such ground vibrations could conceivably be destructive to structures by seismic shaking of the foundation rather than by acoustic shaking of the walls and windows.

This problem was, therefore, studied both theoretically (reference 44) and experimentally (reference 85 and 86) with the following general conclusions:

1. The ground particle velocity of seismic waves in response to sonic booms can be "predicted" with good accuracy on the basis of classical theories of elastic behavior of the ground.

2. The maximum ground particle velocity is of the order of 0.1 millimeters per second for each psf of sonic boom over-pressure.

3. The damage potential of peak particle velocities induced by sonic boom is well below damage thresholds accepted by the U.S. Bureau of Mines and other agencies based on their accumulated experience with mining and blasting activities.

Another terrain effect which has been considered is the triggering of mini-avalanches. Accordingly, a series of 16 supersonic flights were made over the area of Star Mountain, Colorado (reference 87) with over-pressures ranging from 1.5 to 5.2 psf. No avalanches were caused by the sonic booms, although during the same period one avalanche was induced by high explosives and a second was released by unknown causes. These tests were inconclusive, however, because Forest Service personnel rated avalanche hazard "low" during the test period.

Underwater Effects

Concern for the effects of sonic boom on fish and plant life in the oceans and lakes have also resulted in both theoretical and experimental studies of sonic boom penetration into water (references 88, 89, 90 and others). These studies are all in essential agreement that most of the sonic boom energy is reflected at the water surface back into the atmosphere. The part that is transmitted into the water when the generating aircraft is flying at speeds less than Mach 4.4 (reference 91) does not have the abrupt initial

and final shocks characteristic of the airborne signal, and also attenuates rapidly with depth. (Aircraft traveling at $M > 4.4$ produce signals in the water that retain the sharp initial jump and which attenuate very little with depth). It is generally agreed that the pressures induced by any anticipated sonic booms will be negligible compared to normal wave action (2 psf corresponds to a wave height of 0.4 inches) or to noise induced by a passing ship, so that no harm to marine life is considered possible.

Conclusions

The following general observations based on current state of the art can be made.

1. By far the largest percentage of sonic boom damage claims payments has been for glass damage. Plaster damage ranks second.

2. Some structural responses can be more closely correlated with the impulse of the pressure signature than with the peak over-pressure.

3. The direction of boom propagation in relation to the orientation of a structure or structural element is very important to its reaction.

4. Sonic booms having over-pressures in the range from about 3 psf to about 5 psf can cause minor damage to the following structural materials: plaster on wood lath, old gypsum board, old bathroom tile, a new suspended ceiling that has already been damaged and new stucco.

5. For sonic booms generated during normal cruising flight, considering all flight paths and the typical 1 psf over-pressure, breakage is anticipated at 68 per million exposed panes due almost entirely to already cracked windows.

Breakage rate of "healthy" glass under the same conditions would drop to 1 per million panes.

6. The effects of sonic booms on other aircraft, both in flight and on the ground are negligible, except for the case of a very close fly-by resulting in extremely large over-pressures, in which case the effects are noticeable, but still very minor.

7. For N-wave over-pressures larger than 2 psf, it may be necessary to take nonlinear effects into account when attempting to predict window response to sonic booms.

8. Systems with essentially high-frequency response characteristics will be primarily sensitive to peak over-pressure and not to the duration of the sonic boom pressure signature. Low frequency systems will be sensitive to both duration and peak over-pressure.

9. Further investigation is necessary to determine the potential of sonic booms for triggering avalanches.

10. Seismic effects resulting from sonic booms are well below structural damage thresholds.

11. The pressures induced underwater by sonic booms attenuate very rapidly with depth and do not constitute a threat to marine life.

Animal Response

It has been claimed by farmers and livestock breeders that supersonic flight programs over their property has resulted in economic damage. Primary complaints were that the productivity of animals was adversely affected by the startling effect of a sonic boom and that panic and injury often resulted from the startled reaction.

Controlled investigations of animal response to sonic boom began in 1965 with study of the effect of hatchability of chicken eggs. It was resumed in 1967 when the response of farm animals to sonic booms was studied as part of the Edwards Air Force Base sonic boom experiments. Subsequent studies (references 92, 93 and 94 in 1968 to 1972) were concerned with the response of cattle and horses to extremely intense booms (80 to 144 psf), with effects on fish and on raindeer, mink and fish eggs.

Damage claims data compiled during the years 1961-1970 totalled about $900,000 for claims received and $128,000 for amount awarded (reference 93). By far the largest amounts claimed and awarded were connected with mink production $610,000 and $100,000, respectively), with claims for chickens and horses following a distant second and third in importance. These amounts are quite small compared with amounts claimed and received for damage to structures from 1956 to 1970, which were 30 6 million and 1.7 million dollars, respectively.

No significant responses or production changes by horses, dairy cattle, beef cattle, sheep, turkeys, chickens or pheasants were found.

As a result of the large number of damage claims involving mink, two extensive investigations of mink response (reference 95 and 96) were made. On the first investigation, the sonic booms were simulated by a pair of compressed air driven shock generators coupled to a large exponential speaker horn. Subjectively, the pair of pulses radiated from this horn sound like a real sonic boom and could be delivered at over-pressures ranging from 0.5 to 2.0 psf when positioned in the vicinity of the mink. Exposures of female mink were begun just after breeding and ended after the youngest kit (baby mink) was 11 days old. A similar control group of animals was not exposed. Fertility rate of exposed females

was found to be considerably higher (95% versus 78%), mortality of boomed kits was higher and overall production was higher for boomed mink. No evidences of nervous reactions in the mink or connection with kit mortality could be ascribed to the sonic boom exposures.

Mink farmers questioned the tests on the basis that they were simulated and that females had time to adjust to the sonic boom exposure program prior to whelping. For this reason, a second experiment was conducted using both simulated booms and actual sonic booms, delivered at 3.6 to 6.6 psf. Three booms were delivered over a 60 minute period by either the aircraft or the simulator. In each case the exposure was made on the day that approximately 40% of the females in each group had whelped. Control animals were not boomed. No adverse effect on reproduction or behavior resulted from the booms.

Hatchability of Chicken Eggs

Two principal experimental investigations into the effect of sonic boom on hatchability of chicken eggs have established that sonic boom exposures have no influence on this process.

The first study, (reference 97) carried out in Texas, exposed five sets of hatching eggs, totaling 3,415 to approximately 30 booms per day during different portions of the 21 day hatching period. Three additional sets of eggs were used as controls and were not exposed. Over-pressures inside the incubators during the first 12 days, ranged from 0.75 to 1.25 psf (requiring 4 to 5 psf over-pressure outside the hatchery buildings). During the final 9 days, exterior over-pressures were raised to 17-19 psf, for a total count of 600 booms during the entire hatching period. The mean hatch rate of all exposed sets was 84.2% as against 83.2% for the control set. No developmental deviations were found

in sample birds examined during the test.

Another study (reference 98) carried out in France exposed chick embryos to six sonic booms per day during the hatching period. It was found that the chicks from these eggs were normal.

Fish

Fish eggs reached a critical period at a certain stage during their development where they become sensitive to vibration or disturbance. This has resulted in programs designed to determine if the disturbances caused by sonic booms generated during overwater flight could have a detrimental effect during this period and other periods.

In one program (reference 99), trout and salmon were reared from the egg stage onward in the usual manner except for exposure to sonic booms in the 1 to 4 psf range. No increase in mortality as compared to a control group could be detected.

Another program (reference 100) studied the response of guppies, to very intense shock waves (550 psf in air) delivered by the over-flight of high speed rifle bullets in a ballistic range. The fish usually reacted to the passage of the shock wave, but only momentarily and they did not appear to be alarmed. No adverse effects due to the boom were observed during two subsequent months of observation.

Wildlife

Two important studies are on record regarding the reaction of wildlike to sonic boom. One of these was carried out in Sweden (reference 101) to monitor the behavior of raindeer, which are considered to be much more nervous animals than cattle, horses or other domesticated animals.

A group of 24 male and female raindeer were confined to a corral in Northern Sweden and their behavior recorded on moving picture film. At low levels (0.3 to 0.5 psf) the animals reacted with temporary general muscle contraction and with minimal or undetectable interruption of activities. Higher levels (up to 10.5 psf were carried out) had stronger effects - animals raised their heads to look around and sniff before returning to previous activities, but never strong enough to bring resting animals to their feet. No panic movements were observed, but no adaptation to startle was noted either.

One unplanned incident has been reported (reference 102) involving the mass hatching failure of Sooty Terns in a breeding colony on Bush Key off the coast of Florida. A nearly continuous record of the colony has been kept since 1903 by the National Park Service. During years preceding and following 1969 the annual birth rate of young terns was estimated at 25,000 to 30,000. However, in 1969 only 300 to 400 young were born. Many possible causes were investigated, including: weather, predation, food shortage, overdense vegetation in the colony, pesticides, and disturbances by man. All of the first five possibilities were rejected as explanations in the given circumstances. No record of aircraft landings in the neighborhood (which are unauthorized) exists, but it is known that overflight by aircraft flying below 500 feet invariably trigger mass panic flights of the Sooty Terns. However, the birds usually return to their nests within 10 minutes and no harm is done to the eggs. However, National Park Service personnel report that three very intense sonic booms were experienced in the neighborhood between May 4 and May 11 (several windows were broken and crumbling mortar was dislodged from buildings on adjacent Keys). It was concluded that the severe sonic booms caused by low-level "on-the-deck" supersonic flights to which the colony may have been exposed were the most likely cause of damage. Booms generated by an aircraft flying supersonically within 60 feet of the ground

have produced over-pressures of 100 psf or more. Booms caused by high flying aircraft passing over the Dry Tortugas subsequently have not produced any repetitions of the 1969 incident.

Two ideas were advanced by Robertson as to the effects of the booms: death of the embryos from exposure due to abandonment by the colony in panic flight or physical damage to the eggs that were not covered by a sitting bird at the time of the boom. (On the day the most severe shock occurred, the weather was warm and sunny, so that the birds did not incubate and most of the eggs were probably directly exposed to the sonic boom.) The author stated that although the case is circumstantial, the possible physical damage to the eggs most adequately explained the available facts.

Conclusions

The following are some general conclusions concerning the present state of knowledge of animal response to sonic booms.

1. Animal damage claims are only a very small fraction of the total damage claims that have been submitted to the Air Force.

2. The behavioral reactions of farm animals to sonic booms are, for the most part, minimal.

3. All experimental evidence to date indicates that the exposure of mink to sonic booms does not affect reproduction.

4. All experimental evidence to date indicates that the exposure of chicken eggs to sonic booms does not affect their hatchability.

5. Sonic booms do not appear to pose a threat to fish or fish eggs.

6. Knowledge concerning the effects of sonic booms on wildlife is limited and except for the Sooty Tern incident, with its most unusual flight manouver, it appears that sonic booms do not pose a significant threat.

8. Threshold Mach Number Operations

The term "threshold Mach number operation" of aircraft refers to a concept whereby an airplane could be flown at supersonic speeds relative to speed of sound at flight altitude and still avoid the laying down of a sonic boom at ground elevations.

It has long been observed that under suitable weather conditions the sound from explosions set off on the ground may be heard from great distances away, but often the sound is completely inaudible over large regions much closer to the source. This phenomenon has been studied and understood in reasonable depth for about a hundred years. It was seen that the vertical variation of sound speed and wind speed acts like a lens to refract the sound into curved paths that could amplify the sound in some regions and eliminate it in others.

This tendency of the normal atmosphere to bend sound rays away from the ground has provided the incentive to study the conditions under which sound waves from a supersonic airplane would start on their downward path, but then curve away from the ground and ultimately dissipate back into the upper atmosphere. Figure 8.1 shows a sequence of 4 successive moments in a supersonic airplane beginning with snapshot 1. This shows the aircraft at the instant that a ray of sound is emitted from the neighborhood of its tip. (This is a highly overidealized picture of the pressure field in the neighborhood of the airplane, but becomes more precise for succeeding snapshots.) In the second snapshot, the ray has reached 2 (on the shock surface) while the airplane has arrived at position 2. The ray is approximately perpendicular to the shock surface at its point of touching. In snapshot 3 we note that the ray is leveling off towards the horizontal and that the shock at the intersection is becoming more vertical. In snapshot 4 the ray is horizontal,

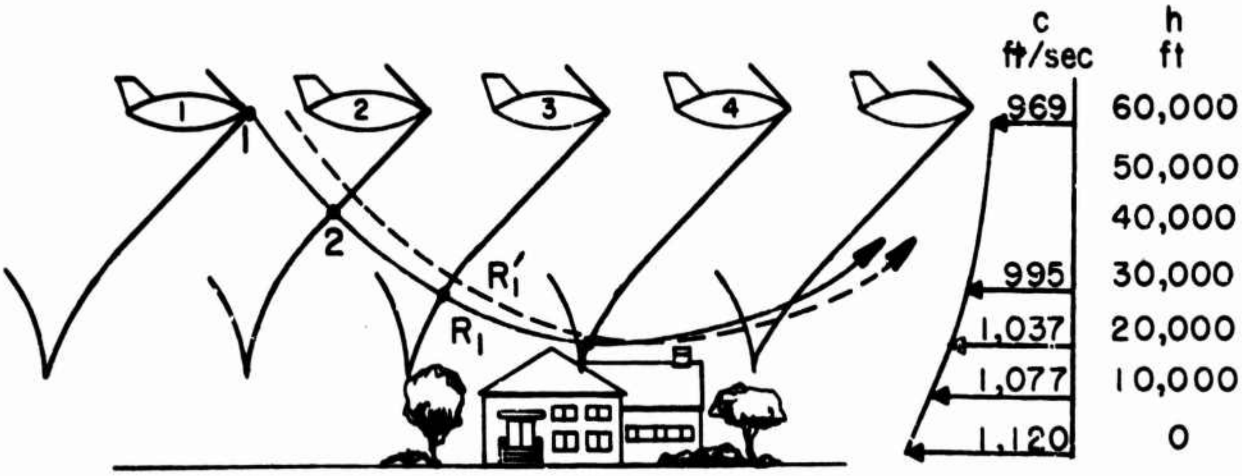


FIGURE 8.1
PATH OF RAYS AND SHOCKS DURING
THRESHOLD MACH NUMBER FLIGHT

so that the local shock orientation is vertical. The subsequent history of the ray is very complex. Since the ray does not reach below the lowest point as achieved in snapshot 4, the amount of sound energy to be found at elevations below the surface of lowest ray points should become zero, according to the above line of argument. Furthermore, if we regard two adjacent rays R_1 and R_1' in the figure, we see that those rays merge on the surface of crossings formed by the turning rays, so that all of the energy in the volume between the rays is focussed onto that surface (called the caustic surface). The resulting acoustic intensity should therefore, become infinite on the caustic surface.

The above picture is modified in reality by the nonlinear behavior of waves travelling in air, which prevents the formation of regions of infinite acoustic intensity and by the essential complexity of the acoustic fields which leak over from the zone of full "illumination" into the "shadow zone". Thus, the experience with this phenomenon is that the over-pressures in the region of the caustic surface generally rises by a factor varying between 1.8 and 1, and that the shock over-pressures beneath the caustic surface drop off rapidly at distances of the order of 300 feet.

The above shock refraction phenomena is the basis for the interest in what has been termed "threshold Mach number operations". Because of this refraction, if the speed of the airplane is somewhat less than the speed of sound at ground elevation, no shock wave will penetrate to the ground even though the airplane speed is greater than the speed of sound at flight altitude.

Studies of threshold Mach number flight have, therefore, been carried out which have dealt mainly with three areas of concern:

1. Variations in threshold Mach number due to variations in meteorological condition (references 14, 16 and 103);

2. Nature of the pressure signature in the vicinity of the caustic (reference 30); and

3. Feasibility of boomless supersonic flight (reference 104, 105 and 106).

The basic mathematical statement of the condition for threshold flight is given by:

$$M_T = \frac{V_T}{C_a} = \frac{(C+U)_{max} - V_a}{C_a} \qquad \text{where}$$

M_T = threshold Mach number to avoid sonic boom

V_T = airplane speed corresponding to M_T

C_a = speed of sound at flight altitude

U_a = tailwind speed (negative if headwind)

$(C+U)_{max}$ = maximum value of the sum of sound speed and tailwind existing anywhere beneath the flight altitude and is also equal to the maximum ground-speed of the airplane.

This formula modifies the refraction concept due to variation of sound speed, to include the additional refraction due to wind speed variation.

In a normal atmospheric condition, the speed of sound drops continuously as altitude increases, until stratospheric altitudes are reached. In conditions of temperature inversion the maximum speed of sound (which depends only on temperature) will be greater than that existing on the ground. Under favorable conditions flight Mach numbers as high as 1.3 can be achieved (reference 105).

Statistical studies of weather conditions on a San Francisco/New York route were carried out (reference 106 and 103) for an airplane altitude of 45,000 feet, under winter, summer and annual weather conditions. Mean threshold speeds corresponding to observed conditions were calculated. The table, Figure 8.2, summarizes some results:

Airplane Altitude of 45,000 Feet

	95% Probability of Being Greater Than	50% Probability of Being Greater Than	5% Probability of Being Greater Than
Westbound (Headwind)			
January	1.140	1.185	1.250
July	1.175	1.210	1.260
Annual	1.155	1.200	1.250
Eastbound (Tailwind)			
January	1.020	1.050	1.090
July	1.060	1.110	1.155
Annual	1.035	1.080	1.140

FIGURE 8.2
MOST PROBABLE AND EXTREME ROUTE MEAN SAFE THRESHOLD MACH NUMBERS FOR SAN FRANCISCO TO NEW YORK CITY ROUTE (FROM REFERENCE 106)

This table shows that the predominant west wind variation raises westbound flight threshold Mach numbers and lowers eastbound threshold flight Mach numbers. The average annual allowable flight Mach numbers for westbound flights are seen to be between 1.155 and 1.250 for 90% of the time and exceed $M_T = 1.155$ for 95% of the time.

These route mean safe speed data were used to compute travel times for boomless supersonic flight. It was found that a travel time of 4.0 hours or less (compared to typical subsonic travel times of about 5.2 hours)

could be flown almost 100% of the time during eastbound flights and about 70% of the time for westbound flights. (Although cutting down the allowable Mach number on eastbound flights, the tailwinds still increase the allowable ground speed).

Studies of the behavior of the sonic boom in the vicinity of the caustic surface have been made using the instrumented 1529 foot tower at Jackass Flats, Nevada. The following Figure 8.3 shows the appearance of typical sonic boom traces as experienced by microphones at various elevations. Thus, above the caustic there was noted a sonic boom with well defined shock fronts. The lower microphones show the booms deforming to generate two well defined spikes with over-pressure roughly double that of the original shocks, with U shaped signature between the peaks and with a definite "precursor" region preceding the spike. As the elevation drops the microphones pick up a rumbling noise that has lost almost all resemblance to the original shock signatures.

Conclusions

The following are some general conclusions concerning flight at the threshold Mach number:

1. Amplification factors near the caustic produced by steady level flight at the threshold Mach number are in the range from 1 to 1.8.

2. The sound field heard at elevations beneath the caustic are characterized by a rumbling sound with slow rise and fall.

3. Block times for threshold flight over the San Francisco/New York route are on the order of 4.0 hours as compared to 5.2 hours for aircraft which fly subsonically relative to local atmosphere.

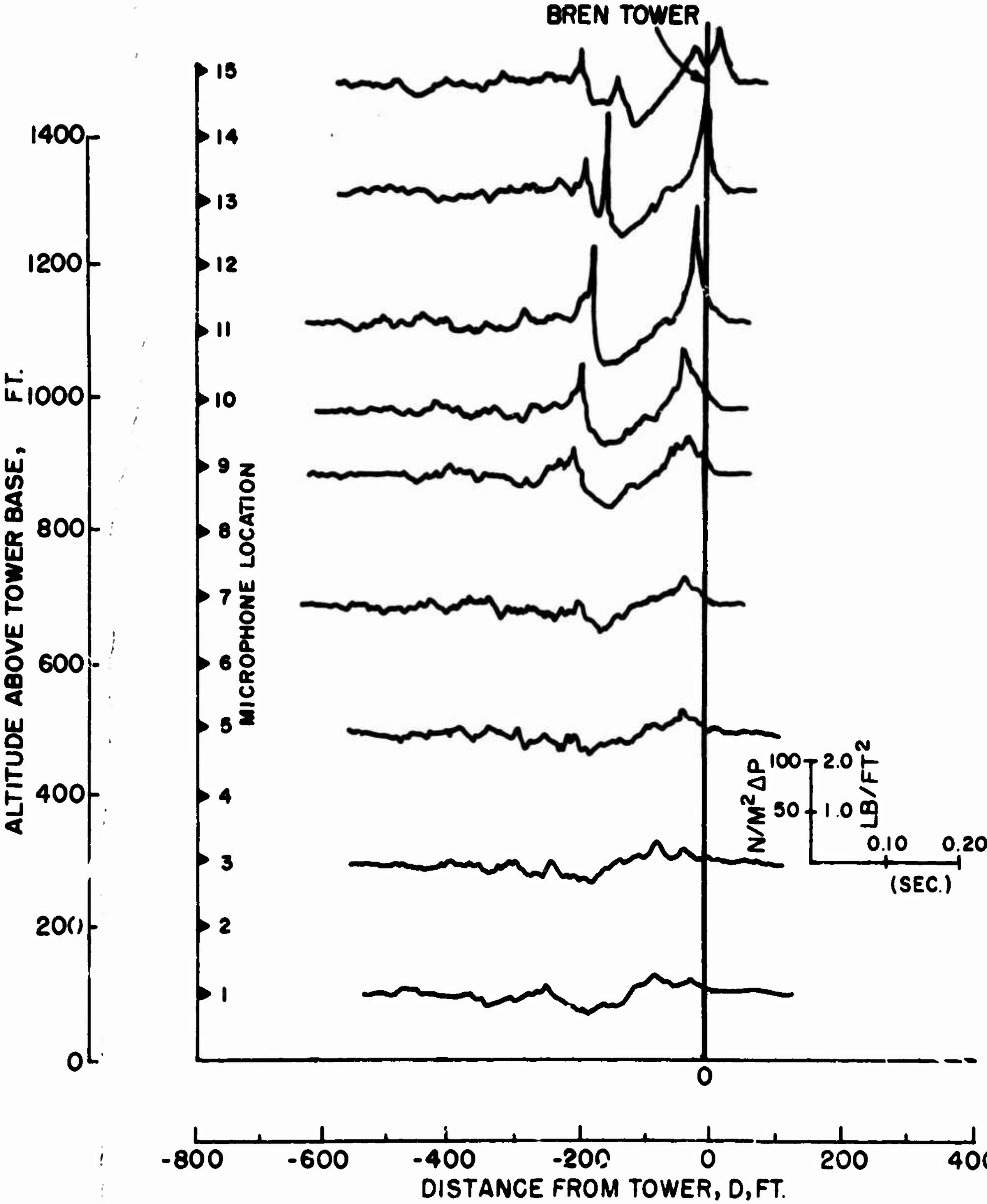


FIGURE 8.3
TOWER PRESSURE SIGNATURES
(FROM REFERENCE 30)

4. Boomless supersonic flight may be feasible if airplanes can be designed to fly efficiently at low supersonic Mach numbers between 1.0 and 1.3.

9. Simulation Methods

A wide range of sonic boom simulation methods have been developed, which allow experimental investigation of almost every aspect of the sonic boom problem, without the use of actual aircraft flyovers. These simulation methods have been based on the use of wind tunnels and ballistic ranges to verify sonic boom generation and propagation theory, explosives and shock driven horns to study structural and human response, pressure chambers and loudspeaker facilities to study human response, as well as others. The basic features of these various sytems are summarized in the following.

Pressure Chambers

Pressure chamber simulation facilities have been used extensively to study human response, including loudness and annoyance, to sonic booms. A number of such facilities have been built at Boeing, Bolt Beranek and Newman, at ISVR in Southampton, England, at Stanford Research Institute and at Lockheed. The Lockheed simulator (reference 77) is typical of these chambers. It has inside dimensions of 41" x 42" x 72" high and heavy soundproof walls. Loudspeakers mounted on the walls can generate signatures having up to 4 psf overpressure and rise time as small as 1 millisecond. The high frequency response (above 1,000 Hz) and low frequency (below 300 Hz) of this type of simulator is difficult to control with precision. Better control is achieved with specially designed earphones which can operate with good control beyond 1,500 Hz.

A pressure chamber which can operate down to very low frequencies is available at NASA Langley, (reference 107) based on a large facility in which one whole wall can be moved like a piston. However, the high frequency response is very inadequate. Similar conclusions apply to the Stan-

ford Research Institute facility (reference 108).

Pressure chamber tests and earphone tests are both questioned because of the unnaturalness of the environment as well as because of frequency limitations.

Travelling Wave Simulators

A true travelling wave can be generated by exploding a chemical charge in space or by bursting a container of high pressure gas. One application of these ideas was developed and used in England (reference 109) based on the use of a number of primacord strands, so distributed and oriented with respect to the target as to give rise to simulated N waves. This explosive array generates a spectrum of acoustic energy which agrees well with that from an actual N wave for frequencies below 100 cycles, but diverges at higher frequencies as a result of the high frequency "roughness" characteristic of sound from solid explosives.

A somewhat related procedure using shaped bags of explosive gas mixture detonated by a single primacord strand running the length of the balloon has resulted in booms of up to 75 millisecond duration and pressures of 3 to 15 psf at 800 feet from the balloon. The signal is much cleaner than that produced by solid explosives.

Several types of conical shock tubes have been developed for sonic boom simulation. The first, developed in England (reference 11, 110) is called the "Blunderbuss", an acronym for Bloody Loud Uncommonly Noisy Device Emitting Realistic Booms Using Something Simple. This produces an N wave by bursting a diaphragm in a shock tube, modifying the shock shape in a long cylindrical tube and then expanding into a conical horn. Another system (112,56) tailors the shock signature propagating in a large conical duct by means of a compressed air metering valve located at the apex.

N wave durations of up to 500 milliseconds can be reached. The rise time and shape of the resulting signatures are also controllable and mathematically related to the choice of compressed air metering rate. These systems have been employed for the investigation of human response to sonic boom (reference 56) and of the structural behavior (including crack propagation) of large (8' x 12') building wall panels (reference 113).

Another type of facility has been employed for structural and acoustic studies of small scale models of complete buildings (reference 114). This facility is based on the classical observation in "The Dynamical Theory of Sound" by Horace Lamb (reference 115), that the sound field produced by a bursting spherical balloon is a perfect N wave of duration proportional to the diameter of the balloon. The same N wave can be conveniently generated within a cone by pressurizing a small region near the apex, using a cellophane diaphragm to take up the pressure (Figure 9.1.) provided by a compressed air source. The pressure in the driver section is allowed to increase until the diaphragm bursts. The wave that then travels down the cone is a true N wave which can then be made to strike a small scale model placed near the end of the cone. Comparison with full scale tests (reference 116) has shown that the data from the small scale tests can be applied to the prediction of full scale results, with quite remarkable accuracy, insofar as acoustic responses are concerned. Structural vibrations are more difficult to predict with precision because of the difficulty of scaling ordinary architectural materials and construction procedures down to small size.

The above bursting diaphragm concept has been used on a much larger scale in France, at the Institut Franco-Allemand de Recherches de Saint-Louis, (reference 117). In this facility the driver section is big enough to create a 300 foot long sonic boom, with extremely clean pressure

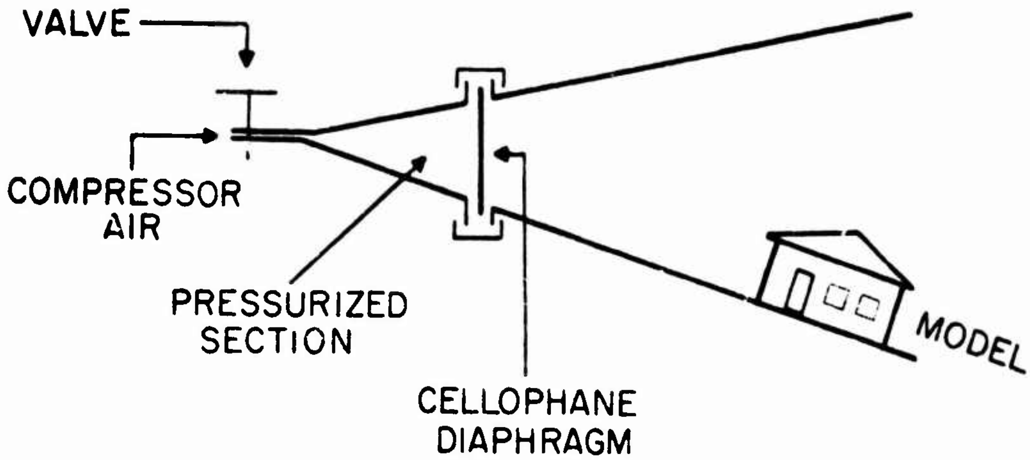


FIGURE 9.1
FACILITY FOR SIMULATING SMALL SCALE
SONIC BOOM CONFIGURATIONS

signature (the valve type facilities of references 112 and 56 generate a hissing noise which some auditors find distracting). The test section is large (8 1/3' x 8 1/3') and suitable for both structural and psychocoustic tests under a large range of over-pressures.

Another device for sonic boom simulation is the acoustic horn (reference 118) which is used to radiate a pair of acoustic pulses created with shock tubes. The resulting signals can be made to sound like sonic boom, and so can be used for psychocoustic studies, but its utility for studying structural responses is limited.

Ballistic Simulation

Ballistic range simulators operate by firing a high speed projectile down a suitable firing range. The shock wave generated by the projectile assumes the shape of an N wave after propagating a sufficiently large distance from the flight path. It is then allowed to impinge on the test area. This type of facility has been used (references 119 and 120) to study sonic boom reflection and focussing phenomena by buildings, interaction with turbulent air and the extent of penetration of shock waves into water.

Wind Tunnels

Wind tunnels have been used to make detailed studies of the pressure field in the near field and far field of aircraft. Since the wave field thus generated is stationary in time, no dynamic effects can be investigated. In addition, far field studies have required the use of extremely small airplane models, with correspondingly small and difficult instrumentation systems. Nevertheless, such facilities have proved very important in establishing the validity of the theories and numerical procedures in sonic boom computation.

10. Some Final Comments

It is hoped that the foregoing pages capture the flavor of the main technological concepts which have been at work in the field of sonic boom studies. Although the sources referred to are fairly extensive, they are by no means exhaustive. In each of the subject areas touched, it would be possible to reference and comment upon at least as many more ideas and contributions as herein noted. In addition, the output of work has been continuing beyond the date of the sources reviewed herein, in response to the continued interest generated by the Anglo-French and Russian supersonic transport programs.

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